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STRUCTURE OF GAS TURBINE FUEL SPRAYS

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Structure of Gas Turbine Fuel Sprays

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ABSTRACT

The gas turbine fuel injector has been the focus of considerable on-going research and development for over fifty years in order to satisfy the continuously evolving requirements with regard to combustion performance, fuel consumption and pollutant emissions. This exposition attempts to summarise the principal findings from the author's own research during the past two decades, and to identify their significance within the global framework of related studies in the area of gas turbine fuel injection. His recent studies on the structure of sprays in the near-nozzle region, encompassing simplex, pressure-swirl and engine-standard, pre-filming airblast atomizers, are characterised by an unparalleled combination of near-full power air density and liquid throughput, thereby extending significantly the knowledge database on the performance of these nozzles. They also served to reconcile the long-standing apparent contradictions in the open literature concerning the effect of ambient air pressure variation upon spray SMD for the simplex swirl injector. Moreover, they showed for the first time that the near-nozzle spray trajectory and overall mean drop size characteristics of the types of airblast nozzles used on engines are significantly different from those of the laboratory-scale atomizers featured in earlier research efforts. This is a reflection principally of the distinctive nature and scale of the fuel-air interactions involved in the two different environments.

The new knowledge and understanding generated by the author's work on the plain-jet airblast concept has found practical application in large-scale industrial gas turbine engines. It is also contributing to the design of certain hybrid fuel injector configurations, which are now being offered either as an alternative to or in combination with the more established pre-filming concept.

The limit of capability of both the laser sheet imaging technique developed by the author and the commercially available phase Doppler instrument have, for the first time, been successfully explored at the extreme conditions of high air density and high fuel throughputs encountered in modern gas turbines - yielding generally plausible isothermal spray property data.

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1. INTRODUCTION

Liquid-fuelled gas turbines have been the subject of on-going evolution ever since their introduction as a power plant for aircraft and industrial applications. The fuel injector has throughout played a pivotal role in the attainment of the appropriate combustor performance goals. When faced with new and sometimes daunting challenges, the combustion engineer has traditionally expected the fuel injector to deliver the necessary solutions, either in its current guise or through the development of new design concepts [1]. Some of the key drivers underpinning fuel preparation research over the years are enumerated below:

- Increases in the maximum power operational envelope of the combustor, resulting in steadily increasing inlet air pressure and temperature and injector fuel throughput.
- Satisfactory altitude re-light and pull-away capability at simultaneously low injector fuel flows and low combustor air pressures. In combination with the maximum power requirement, this implies the need for injectors with an appropriately large turndown capability [2].
- Injectors incorporating fuel-flexibility, either to alleviate emergency shortages, or to mitigate potential relaxation in specifications resulting in the prolonged use of heavier, higher-viscosity, reduced-volatility fuels [3].
- Compliance with progressively tightening regulations in respect of gas turbine combustion-generated pollutants. This has led to refinement of the existing configurations, as well as the development of alternative low-emission concepts [1,4]. In consequence, added emphasis has been placed on improvements in fuel-air mixing which can, under certain conditions, generate fuel-injector induced instabilities, as recently experienced in lean direct injection combustors [5,6].

- Innovative designs incorporating better thermal management of the input heat flux generated by the increasingly hostile ambient air pressure and temperature environment surrounding the fuel injector [4,7].
- Trend towards shorter and more cost-effective combustor development cycle times requiring a better grasp of the still poorly understood coupling between fuel injector design, simplistic spray performance and the prevailing flow-field within the primary zone. In addition to the obvious need for more ‘tailored’ injector designs, this calls for the development of appropriate diagnostic tools, as well as their evaluation to reliably probe the increasingly harsh practical environments with which the injector has to contend.

This commentary deals with the structure of fuel sprays, which is widely acknowledged to play a crucial role in many of the basic processes involved in gas turbine spray combustion [2,8]. The relevance and significance of the author’s publications submitted in support of this exposition are described in the sections that follow, together with the context for these contributions. However, this review has deliberately been undertaken not on a paper-wise basis, but along the broad themes addressed by the submitted research work in its entirety. It was felt that this approach would result in a more cohesive and meaningful discussion of the acquired insights and their significance. The broad themes addressed by the research undertaken have been categorised as the **operability factors**, and the enabling technology topics of **nozzle design** and **spray diagnostics**.

2. OPERABILITY FACTORS

Appreciable increases in the operating air pressure and fuel flow envelope of the gas turbine combustor, combined with the need for fuel-flexibility in the event of an embargo on Middle East oil supplies, provided the motivation for the early studies undertaken by the author. Pressure-swirl atomizers of the simplex and dual-orifice type were then in widespread use, but growing problems of exhaust smoke at high combustion pressures eventually led to their replacement with the pre-filming airblast atomizer which had been under extensive development at Cranfield during the 1960s [9-12]. More recently, however, the pressure-swirl atomizer has had a new lease of life through alternative uses - for example as a means of delivering fuel on to a cylindrical surface within a swirl-cup arrangement conveying swirling airstreams to the combustor primary zone of the F101, CFM56 and CF6-80 engines [13]. The vaporizing style of fuel injector was a serious rival at the time to the airblast injector, due to its use in many Rolls-Royce engines, including the RB199 fitted to the Tornado strike aircraft [14-15]. In recent years, the vaporizer has fallen out of favour due to concerns surrounding its durability in the new generation of high-pressure-ratio engines. This section discusses the author's work in respect of the effect of the operability factors of fuel viscosity, fuel flow rate and ambient air pressure on the structure of sprays produced by pressure-swirl, vaporizing and airblast fuel injectors under isothermal conditions.

2.1 Pressure-Swirl Atomizer – Simplex.

2.1.1 Effect of Operating Fuel Viscosity

The study entitled 'Atomization of Crude and Residual Fuel Oils' reported in Submitted Paper (SP) 1 featured experiments covering a very wide variation in fuel viscosity on three nozzles of differing flow numbers. Prior to this work, Radcliffe [16,17] and Koblish and Schwartz [18] had explored the behaviour of simplex swirl atomizers. The range of actual viscosity levels covered, however, was not outlined in their own publications. In reality, Radcliffe had analysed the work reported by Joyce [19], which as described by the author himself, featured '*some preliminary results*' on the effect of

viscosity variation in the 2×10^{-6} to 18.5×10^{-6} m²/s range at fuel pressures up to 20.7×10^5 N/m² on a single simplex nozzle. The molten paraffin wax method of spray drop size measurement was utilised by Joyce in his research. In addition, the communications reported [20] following Radcliffe's first investigation [16] revealed the existence of some other data on plain holes, of the type used in diesel engines corresponding to a viscosity level of $\sim 6 \times 10^{-6}$ m²/s. These studies appeared to be the only sources of reference available to Radcliffe for determining the impact of fuel viscosity changes on spray quality. From this rather restricted data he deduced that the SMD increased only slightly with viscosity – probably as a function of kinematic viscosity to the power of 0.2 to 0.215. Due to the preliminary nature of the experimental data available, and the relatively small range embraced by it, there clearly was appreciable cause for concern regarding its applicability and reliability in situations featuring higher fuel viscosity levels.

The work described in SP 1, featuring a laser diffraction instrument, was the first and most comprehensive investigation exploring the relationship between fuel viscosity and atomization quality for simplex nozzles. The prevailing concerns were appreciably mitigated through the author's provision of an extensive and relevant database that enabled the spray SMD to be more accurately correlated against fuel viscosity for highly refined kerosene through to low-grade residual fuel oil. The range of viscosity and fuel pressure drops covered by the author were respectively five times and one and a half times those alluded to in Joyce's study [19]. In actual terms it embraced a viscosity range of 1×10^{-6} to 93×10^{-6} m²/s compared with 2×10^{-6} to 18.5×10^{-6} m²/s, and pressure drops up to 3500 kN/m^2 as opposed to 2100 kN/m^2 . This work revealed that the earlier predictive relationships [17,18] were satisfactory when restricted to low-viscosity, kerosene-type fuels but became increasingly inaccurate as the fuel viscosity levels were raised – over-predicting by around 75 to 100 per cent at the higher levels. The acquired database was used by the author to develop a mean drop size correlation of improved accuracy, ca. ± 25 per cent, principally from the standpoint of SMD – viscosity, ν , dependency, which was found to satisfy the relationship $\text{SMD} \propto \nu^{0.16}$. Moreover, the correlation proposed was valid over the full range of liquid viscosity and fuel pressure

drop levels featured in the investigation. The overly pessimistic nature of the earlier relationship, as revealed by this work, meant that the impending challenge of alleviating the effect of fuel viscosity increase on spray performance was likely to be less onerous than had been anticipated. Subsequent investigation by Dodge and Biaglow [21], albeit featuring lower levels of viscosity (up to $5.5 \times 10^{-6} \text{ m}^2/\text{s}$) on simplex swirl atomizers, came up with the relationship $\text{SMD} \propto \nu^{0.136}$, thereby providing support for the author's earlier research. The extensive viscosity range embraced by the author's work remains unparalleled to date.

2.1.2 Effect of Operating Air Pressure and Fuel Flow Rate

The effect of ambient air pressure variations on penetration and cone angle of the sprays produced by simplex swirl atomizers was reported in SP 8. De Corso and Kemeny [22] had previously investigated this particular aspect on light diesel fuel sprays, at a single far-field distance of 115mm from the nozzle exit for air pressures up to 8 bar. Neya and Sato explored the effect of changes in ambient air pressure, up to a maximum of 5 bar, on the far-field cone angle behaviour at a solitary position located 200mm from the nozzle exit for swirl atomized water sprays [23]. Near-nozzle cone angle behaviour under conditions of varying ambient air pressures was investigated by Dodge and Biaglow [21]. Their work, however, was restricted solely to the very near-nozzle distance of 10mm from the injector exit, at which location a relatively small change in spray cone angle was observed – circa 10% of the baseline value as ambient air pressure was raised from 2 to 13 bar.

The author's work, SP 8, featured air pressure variations up to 14 bar, while the focus on penetration behaviour of kerosene sprays was restricted to a maximum axial distance of 45mm from the face of the injector. Since most combustors generally operate at relatively high air densities and feature compact primary zones that are typically around 50mm long, the author's chosen combination was clearly more representative of the combustor primary zone environment. The far-field cone angle collapse reported earlier, [22,23], was confirmed as being prevalent in the near-nozzle regions studied by the author. In addition, it was established that the contraction of the spray boundaries

with increasing ambient air pressure occurred at a faster rate initially, followed by a levelling-off around the 10 bar air pressure level. Dodge and Biaglow's work implied that within the very near-nozzle region, fuel momentum exercised a dominant influence upon the spray cone angle and penetration. This was confirmed by the author's observation that the initial trajectory with which the liquid left the injector orifice was practically unaffected by ambient air pressure variations. However, the evolution further downstream was found to be a reflection of the on-going interaction between the cone-shaped, spreading liquid sheet and its surrounding air environment. At the near-nozzle location of 10mm, this interaction had not built up to a sufficient extent to cause much change in cone angle and spray cross-sectional area, even at 12 bar ambient air pressure. At the 30mm location, however, the cumulative interaction was much more pronounced, resulting in an appreciable collapse in cone angle and a corresponding reduction in spray cross-section at the same air pressure. Raising the ambient air pressure from 1 to 12 bar, for example, led to a reduction in cross-sectional area of the spray by 25 and 75% for the respective downstream distances of 10 and 30mm from the nozzle exit, as featured in the two studies. The author's study provided the clearest understanding of the cone angle and spray trajectory changes as a function of ambient air pressure variations in the crucially important, near-nozzle region. Analysis of the observed effect of ambient air pressure variation, P_a , upon spray dimensions at an axial distance of 30mm from the injector face revealed radial penetration of spray as being proportional to $P_a^{-0.26}$. This important and new capability to predict spray penetration under conditions of varying ambient air pressure, at a location fully representative of typical primary zone length, allows better evaluation of the extent of matching between the fuel and air flows within a given combustor configuration featuring simplex pressure swirl atomizers. Clearly this has potential implications for the combustion and emissions performance of such systems.

The relationship between spray quality and ambient air pressure was studied recently by the author and is reported in SP 23. Previous studies had focused primarily on the overall spray mean drop size and, in general, there have been some notable inconsistencies with regard to the observed influence of ambient air pressure upon

SMD. The effect on spray mean drop diameter of variations in ambient air pressure to 8 bar was studied by DeCorso for pressure-swirl nozzles [24,25]. Measurements were made at a distance of 185mm from the injector exit using a photographic technique employing light transmission-shielding tubes. Under some conditions overall spray SMD was observed initially to decrease with rises in ambient air pressure, followed by an increase as the ambient air pressure was raised further. However, under other conditions a steady increase in SMD occurred as ambient air pressure was raised. Neya and Sato used the immersion method to obtain drop size data along a radius of 200mm from the nozzle exit for ambient air pressures up to a maximum of 5 bar [23]. Spray SMD was found to rise with increases in ambient air pressure. Dodge and Biaglow studied the effect of ambient air pressure variation up to a maximum of 6 bar using a Malvern particle sizer [21]. Drop size data was obtained at a distance of 25mm from the injector exit and experiments were carried out at comparatively high fuel throughputs – ca. 30g/s. An increase in ambient air pressure to 6 bar was found to result in a significant reduction in the near-nozzle spray SMD. At air pressures above 6 bar, however, high levels of laser beam obscuration prohibited the acquisition of any further meaningful drop size data. Wang and Lefebvre also used a Malvern particle sizer to study the behaviour of simplex swirl nozzles under varying ambient air pressures [26]. Drop sizes were measured at a distance of 150mm from the injector exit over the 1 to 10 bar ambient air pressure range. Six different nozzles of low-flow capacity were investigated. Their work on a 90° cone angle nozzle revealed an initial increase followed by a decline in spray SMD as the ambient air pressure was raised steadily to 10 bar. From the preceding discussion it is clear that the various reported studies exploring the effect of ambient air pressure on the SMD performance of pressure-swirl atomizers have shown conflicting trends. As a consequence, the communicated values of the exponent ‘n’ in the mean drop size versus ambient air pressure relationship, namely $SMD \propto P_a^n$, have exhibited wide variations ranging from +0.27 [23] to –0.53 [21].

The author’s work, SP 23, featured experiments on a large capacity simplex swirl nozzle at air pressure levels of 1, 8 and 12 bar. A second generation Phase Doppler Interferometry, PDI, instrument was used to explore the dense spray structure in

detail at a distance of 50mm from the injector exit. The nominal cone angle, under atmospheric conditions, was 83° and the liquid flow rate was held constant at 75 g/s regardless of the variations in ambient air pressure. Point-wise, local SMD values at a given air pressure were converted to yield an overall spray SMD using appropriate area and velocity correction factors to account for the differences in flow areas and drop mean velocity levels. Rises in ambient air pressure were observed to yield increases in overall spray SMD, although at the higher air pressure there was a decline in this rate of increase. In a sense this author's observed trend is broadly similar to those of some previous researchers [23-25] and dissimilar to those of others [21,26]. It would appear that these seemingly contradictory trends could be a reflection of the rather complex manner in which a change in air density affects the Weber number and spray cone angle, and hence also the resulting overall spray SMD. This is quite apart from any possible issues that may be associated with the different drop size measurement methods utilised in the various studies.

Invoking Weber number, W_e , considerations (where W_e is defined as a dimensionless ratio of inertia to surface tension forces) concerning the break-up of a sheet of low-viscosity liquid yields:

$$\frac{SMD}{t_\ell} \propto (W_e)^{-x} \quad \dots(1)$$

which for liquids with invariant surface tension simplifies to give:

$$SMD \propto t_\ell^{(1-x)} (u_r^2 \rho_a)^{-x} \quad \dots(2)$$

where t_ℓ is the liquid sheet thickness at break-up, u_r the relative velocity between the liquid sheet undergoing disintegration and the ambient air, ρ_a the ambient air density and x an arbitrary exponent.

If the effect of a rise in ambient air pressure manifested solely through an increase in the air density term in Eq. (2), then SMD would always be expected to decline. This, however, is not the case and there are several other effects that come into play simultaneously. One consequence of an increase in ambient air pressure, as pointed out by Neya and Sato [23], is to accelerate the process by which the liquid sheet disintegrates. This leads to the point of initial break-up of the liquid sheet moving closer to the nozzle exit where the sheet thickness is greater due to the reduced degree of stretching. Ultimately, the sheet break-up could start directly at the nozzle exit once the ambient air pressure exceeds a certain critical value. Eq. (2) shows clearly that an increase in sheet thickness, albeit due to an increase in air pressure shifting the initial break-up point upstream, is exercising an adverse effect upon SMD and thereby serving to oppose the beneficial effect due to an increase in air density.

Another consequence of an increase in air pressure is a reduction in spray cone angle and in turn, the associated spray cross section due to the creation of radially in-flowing air currents. As stated before, the cone angle initially contracts at a faster rate, but eventually stabilises at a certain minimum level beyond which no further cone angle changes are discerned with continuing increases in ambient air pressure. Both DeCorso [25] and Neya and Sato [23] concluded that this reduction in spray cone angle increased the opportunity for droplets to coalesce with each other and thereby afford an increase in spray SMD with rising air density. However, another aspect that is appropriate here, and thus far has received no consideration, is the increase in thickness of the liquid sheet accompanying the cone angle contraction at higher air pressures. This, too, will serve to raise the overall spray SMD as per Eq. (2). Yet another adverse effect, resulting from the decrease in cone angle due to the raised air pressure, is a reduction in the volume of air contained within the core regions of the spray. Consequently, the spray momentum is more readily able to accelerate this smaller volume of air along the general direction of spray motion, thus reducing air to liquid interaction vis-à-vis a decrease in the relative velocity, u_r , and hence a decline in spray quality.

In essence, whether overall SMD increases or decreases as the air pressure is raised is a reflection of the balance between the competing adverse and beneficial ambient air pressure controlled spray processes, initiated concurrently, in a given situation. The eventual outcome is clearly governed by the combined influence of two separate ambient air pressure-dependent phenomena with their own, independent, critical air pressure levels. One is the air pressure at which the spray cone angle assumes its minimum value, while the other is the air pressure at which the sheet break-up starts directly at the injector exit. Further increases in air pressure beyond the two respective critical levels would not be expected to influence either of these two processes. Therefore, a reduction in overall spray SMD would be expected in principle as the air pressure continues to rise beyond the two critical levels. This assumes that axial penetration behaviour of the spray, which has thus far not been considered, remains unaffected by such increases in air pressure. In practice this is unlikely to be true even in the context of compact primary zones, and consequently secondary processes of droplet coalescence and collisions are likely to exert some further influence on the eventual spray SMD levels. Whilst axial penetration behaviour of pressure swirl sprays under conditions of varying ambient air pressure has not been reported thus far, some support for a reduction in penetration can nevertheless be deduced from the associated droplet velocity distributions. The spatially resolved nature of the author's study provides information regarding the influence of ambient air pressure variation on point-wise distribution of drop mean axial velocities. This does reveal a marked decline in the drop mean axial velocity levels and, in turn, the axial momentum with increases in ambient air pressure. Clearly this particular aspect warrants further research, but the generic arguments expounded in the preceding sections provide a coherent, basic framework for reconciling the apparently contradictory SMD – ambient air pressure trends that are prevalent in the spray literature.

SP 23 study also provides other new and important insights into the detailed structure of the near-nozzle spray under varying ambient air pressure conditions. These are outlined below:

- Increases in ambient air pressure tend to make the spray more homogeneous in terms of the point-wise distribution of mean drop sizes i.e. the radial variation in SMDs diminishes as the air pressure level is raised from 1 to 12 bar. This is also true for other “representative” drop diameters, namely $D_{0.1}$ and $D_{0.9}$.
- The traditional “hollow-cone” structure under atmospheric conditions gradually converts into something more akin to a “solid-cone” spray in which the radial distribution of volume flux is more uniform at higher ambient air pressure levels. This is a reflection of the smaller droplets, due to their lower aerodynamic drag experiencing preferential transportation into the core regions as a result of the inward air movement generated by the spray motion.

Some recent applications of simplex atomizers are to be found in the dome swirl-cup arrangement featured in various General Electric engines (e.g. CFM56, CF6-80) [13] as well as other potential low NO_x research strategies embracing the airblast simplex nozzle [27] and other lean combustion approaches [28]. As is evident from the foregoing sections, earlier research studies have featured comparatively low levels of liquid flow rates and ambient air pressures, (ca. 40 g/s liquid flow at 8 bar maximum air pressure), in relation to the levels consistent with the modern and emerging role for the simplex swirl atomizer. Furthermore, the choice of spray interrogation position has also been inappropriate in relation to the trend towards compact combustor configurations. The special merit of the author’s study is the unique and unparalleled combination of test conditions. Namely that of 75 g/s liquid throughput, 1 to 12 bar ambient air pressure, near-nozzle region droplet property data acquisition (i.e. 50mm from injector exit), and the deployment of a modern PDI instrument with its superior dense spray capability. In consequence, the insights and information generated at conditions of near-full power, practical engine air densities, and liquid throughputs constitute a significant advance from the standpoint of the practising combustion engineer.

2.2 Pressure-Swirl Atomizer – Dual-Orifice

Given that these wide-range atomizers had been used extensively since the early 1950s, the literature contained little by way of research information, with only a brief reference in the work by Simmons [29]. This contained a small amount of SMD data on a typical dual-orifice nozzle featuring a 1×10^{-6} to 12×10^{-6} m²/s viscosity range along with a maximum fuel flow rate of up to 60 g/s under atmospheric pressure conditions. His data revealed an appreciable increase in SMD values corresponding to the point at which the fuel initially flows through the main nozzle and remained high over a significant proportion of the fuel flow range covered. There was, however, no mention of any accompanying effects upon spray cone angle and dispersion.

The author's study 'Dual-Orifice Atomizer Performance under Varying Air Density Conditions', SP 9, focused attention upon the interactions taking place between the pilot and main sprays. It covered a wide range of liquid flows (up to ~ 90 g/s max) and air pressures (1 to 8 bar) using kerosene and gas oil as the test fuels. A combination of conventional, still photography and laser diffraction droplet-sizing techniques was employed. This study was aimed at extending our knowledge regarding the near-nozzle region behaviour of in-service injectors, as well as the acquisition of a practically relevant experimental database to facilitate appropriate action in the event of a relaxation in fuel specifications. Interaction between the two sprays, starting from the instant of initial opening of the pressurizing valve, revealed a wide range of progressively increasing main fuel flows during which the overall mean drop size, cone angle and penetration remained changeable and poor. Whilst the deterioration in drop size performance, corresponding to the initial admission of fuel through the main nozzle had been identified previously [29,30], the considerable range of fuel flows over which spray cone angle and penetration remained poor had not been appreciated. This was especially the case when operating on high-viscosity diesel fuel at atmospheric and higher ambient air pressures. The traditional approach has been to select an appropriate combination of pilot nozzle flow number and pressurising valve opening point to ensure that the range of fuel flow over which spray performance is poor coincides with some transitory engine condition. This restricts to a minimum the degradation in overall

combustion performance. However, the very wide range of fuel flows over which spray performance was found to be generally poor and changeable following the initial introduction of fuel through the main nozzle made this problematic, with potential implications for combustor pattern factor and emissions performance. Furthermore, the simplex pressure-swirl atomizer SMD correlation proposed by the author for the atmospheric case earlier, SP 1, was found to be adequate for the dual-orifice atmospheric data, assuming that the pilot and main sprays coalesced with each other and shared their momenta. Also evaluated was the alternative energy sharing approach but it was found to yield a significantly inferior level of agreement over the critical flow range, during which the combined spray was far from being well formed. The effect of ambient air pressure on combined pilot-main spray cone angle and SMD exhibited trends that were, broadly speaking, akin to those for the simplex swirl nozzles.

2.3 Vaporizing Fuel Injector

By the mid 1980s vaporizer concept had accumulated considerable in-service experience in a number of Rolls-Royce engines in commercial and military aircraft applications. Despite this, and its inclusion in the then-proposed EJ200 engine, little had been published previously by way of research information except the study by Low [31]. This work was aimed at visualizing the vaporizer efflux, using spark photography, under combusting and non-combusting conditions at air pressures and temperatures up to 5 bar and 723K respectively with no fuel pre-heating whatsoever. The extensive development effort was, however, outlined in the reviews by Sotheran [14,15]. Clearly there was considerable ignorance surrounding the precise mode of operation and the nature and quality of efflux emerging from this style of fuel injector. Furthermore, its sensitivity to key operational factors such as fuel viscosity and air velocity, temperature, and pressure was also inadequately explored.

Work reported in SP 11 featured use of high-speed spark photography and laser diffraction droplet sizing. It provided valuable insights regarding the behaviour of vaporizers under non-combusting and combusting conditions at ambient air pressures up to 13 bar, air temperatures up to ca. 600K, and fuel temperatures up to 425K. In addition

to kerosene, gas oil was also investigated in order to address the fuel quality issues prevailing at the time. The efflux was characterised for atomization quality and degree of vaporization as a function of the key operating variables. In essence, this style of injector was found to feature a high degree of atomization and vaporization. In addition, it exhibited spray performance trends that were generally similar in character to those associated with contemporary airblast atomizers, namely an improvement in spray quality with rising injector air-to-fuel ratio and air pressure drop, while increases in fuel viscosity revealed a degrading effect. Whilst this broadly competitive performance was reassuring, there nevertheless was appreciable concern regarding the vaporizer's durability for prolonged operations. In consequence, it was superseded eventually by the airblast atomizer for new engine applications. Despite this, the author's work significantly extended the level of understanding, albeit in the context of the in-service vaporizing injectors.

2.4 Airblast Fuel Injector

2.4.1 Lab-scale Injectors – Effect of Ambient Air Pressure and Fuel Viscosity

The reduction in spray penetration and cone angle encountered with all types of pressure-swirl atomizers at high operating air pressures led to the deterioration of their spray characteristics and, in turn, to poor fuel-air mixing within the combustor primary zone. This resulted in liner durability, pattern factor and exhaust smoke problems. The pre-filming airblast atomizer was developed to mitigate these problems by producing a fine, well-mixed spray of airborne droplets. At the time their spatial distribution was generally believed to be controlled entirely by the prevailing aerodynamics. Early research atomizer designs, generically speaking, incorporated a co-flowing, parallel arrangement between the thin annular fuel sheet and the two, high-velocity, swirl-free encompassing airstreams. Such designs were the subject of in-depth research and development by Lefebvre and his co-workers [10-12, 32-35]. Another form of airblast atomizer, the plain-jet type wherein the fuel was not pre-filmed into a thin sheet but instead discharged in the form of discrete, circular jet(s) into a high velocity airstream, was also studied [36]. Useful engineering correlations had been developed to enable the prediction of spray mean drop diameter over a range of operating conditions [33-36].

However, only Godbole [32] and Rizkalla et al [33] had explored the effect of air density upon spray SMD at the time. Their experiments featured drop size measurements on low viscosity water-kerosene sprays generated by pre-filming atomizers at air pressures of up to ~13 and 8.5 bar respectively and revealed noticeable variation in the value of the exponent for the air density term. The effect of variations in air density on high viscosity sprays, which was adjudged to be of special need [37], had not been explored at all. Consequently, there were considerable uncertainties in respect of the precise effect of air density upon the drop size performance of both types of airblast atomizers, particularly for operation with higher viscosity fuels.

The author's work outlined in SP 1 to 3, systematically extended both the existing knowledge base and its reliability. The initial phase of this investigation was conducted under atmospheric pressure conditions and covered a very wide range of fuel viscosity (up to 0.086 Ns/m^2) - SP 1. The new experimental database generated was extensive and, thus far, the only one of its kind embracing kerosene, gas oil, and other higher viscosity practical fuels including pre-heated, neat residual fuel oil. It also revealed that the SMD performance of the much simpler, plain-jet airblast atomizer was comparable to that of its more complex, pre-filming counterpart when operating on low viscosity kerosene fuel. In addition, the existing pre-filming and plain-jet airblast atomizer drop size correlations [33,36] were found to be broadly satisfactory for use with low-viscosity fuels. However, raising fuel viscosity revealed an increasing scale of over-prediction by the very same correlations relative to the measured values. Although these inadequacies were addressed at the time, there was an urgent need for high air pressure data in order to resolve properly the coupled air density – fuel viscosity issues and their impact on the drop size correlations.

The main distinguishing feature for the subsequent studies, SP 2-3, apart from extending the range of air density covered on low-viscosity fuels, was the hitherto unexplored simultaneous combination of higher air densities and higher fuel viscosity levels. In other words, a combination of $\sim 0.037 \text{ Ns/m}^2$ viscosity at up to and including 14 bar air

pressure. The form of engineering correlations evolved for the two airblast atomizers studied covering a wide range of operating variables are summarised below:

$$\frac{SMD}{D} \propto \left(\frac{\sigma_\ell}{\rho_a V_a^2 D} \right)^{n_1} \left(1 + \frac{1}{AFR} \right)^{n_2} + \left(\frac{\eta_\ell^2}{\rho_\ell \sigma_\ell D} \right)^{n_3} \left(1 + \frac{1}{AFR} \right)^{n_4} \quad \dots(3)$$

where ρ_ℓ, σ_ℓ and η_ℓ are the liquid properties of density, surface tension and viscosity; ρ_a and V_a the density and velocity of air; AFR the injector air-to-fuel mass ratio; D the atomizer characteristic dimension and n_1, n_2, n_3 and n_4 arbitrary exponents.

Eq. 3 can be re-written as:

$$\frac{SMD}{D} \propto \left(\frac{1}{W_{e,a}} \right)^{n_1} \left(1 + \frac{1}{AFR} \right)^{n_2} + \left(\frac{\sqrt{W_{e,\ell}}}{R_{e,\ell}} \right)^{n_3} \left(1 + \frac{1}{AFR} \right)^{n_4} \quad \dots(4)$$

where $W_{e,a}$ and $W_{e,\ell}$ are respectively the Weber number as applied to air and liquid properties and $R_{e,\ell}$ the liquid Reynolds number. The exponents n_1, n_2 and n_4 were found experimentally to have identical values for the two airblast atomizers studied, namely 0.45, 0.5 and 0.8 respectively. Values for n_3 differed only slightly i.e. 0.375 and 0.4 for pre-filming and plain-jet respectively. Whilst from a purist viewpoint, the summative form of the correlation clearly lacked scientific elegance, it nevertheless did have an important role in advancing fuel injector design engineering and technology by ranking the relative importance of the different variables. Furthermore, its origin dates back to the pioneering work of Nukiyama and Tanasawa some sixty years ago [38] and has been subsequently found to be appropriate by other workers, notably Lefebvre and his co-researchers [33-36].

The nature of the $(1 + 1/AFR)$ expression is such that for typical injector design AFRs the difference due to exponents $n_2 = 0.5$ and $n_4 = 0.8$ is small enough to be ignored as a first approximation, thus simplifying equation 4 to yield:

$$\frac{SMD}{D} \propto \left(\frac{1}{W_{e,a}} \right)^{n_1} + (Z)^{n_3} \quad \dots(5)$$

where Z is the Ohnesorge number, Oh , and it simply collates the fuel properties through a ratio of the liquid property based Weber and Reynolds numbers. This reveals the effect of air density to be embodied within the air properties based Weber number, while that of fuel viscosity within the independent Ohnesorge number. The contribution of the Oh number has been observed experimentally to change from one of insignificance for low-viscosity kerosene fuel to that of increasing significance for the higher-viscosity fuels, especially at elevated ambient air pressures because of an appreciable increase in $W_{e,a}$. This explains the markedly different air density effects observed on low and high viscosity fuels and, in addition, provides support for the summative form of the proposed correlating expression. These studies by the author provide, to date, the only experimental evidence for preferring the inclusion of the liquid density term in the Oh number, instead of the air density term as had been the case in some earlier research [33,39].

Previous low-viscosity liquid studies on pre-filming nozzles had revealed an exponent, n , for the air density term in the relationship, $SMD \propto \rho_a^n$, ranging from -0.6 [32] to -1.0 [33]. This was in marked contrast to the value of -0.45 observed by the author in his work featuring an extended range of air pressures on both pre-filming and plain-jet airblast atomizers. Furthermore, these studies [SP 2-3] clarified and established, for the first time, the role of air density in situations featuring higher levels of fuel viscosity – that of accruing an incrementally diminishing level of benefit due to increases in air density relative to the low viscosity case. A clear implication of this finding was that the task of attaining good atomization performance on higher viscosity fuels was going to be appreciably more difficult at low and high ambient air pressures. Given their

inferior volatility characteristics, achieving effective fuel preparation was, therefore, expected to be a formidable challenge. The data and insights generated were deemed to be very timely and valuable, and helped to quantify more accurately the important effects of two key operational variables.

2.4.2 *Practical-scale Injectors – Effect of Ambient Air Pressure and Fuel Flow Rate*

The airblast injectors discussed thus far featured swirl-free (or low-swirl) airstreams that were essentially of a co-flowing, parallel nature relative to the direction of motion of the fuel stream. From around the mid 1980s however, practical injector designs increasingly began to utilise air swirlers to promote higher levels of shear and mixing between the liquid fuel and air streams as an integral part of the mixture preparation process in order to secure further improvements in combustion and emissions performance. In consequence, the liquid sheet is subjected to an intense, turbulent flow-field resulting in its rapid disintegration. This, in turn, leads to a spray with improved mixing and dispersion characteristics. Many parallel efforts have been conducted to acquire a better understanding of the detailed structure of the spray flow-field produced by the so-called practical, engine standard nozzles. In addition to the author, researchers at University of California, Irvine [40,41], United Technologies Research Center, East Hartford [42] and Onera, Toulouse [43] have been the main contributors to this effort. Using the PDI technique, Samuelsen and co-workers have explored the detailed spray structure at air pressures up to 6 bar [40], but the liquid flow rates have been restricted to a maximum of about 10g/s [41]. Others have conducted patternation studies featuring higher liquid throughputs, ca. 30g/s, but the air pressure was maintained at 1 bar [42]. Whilst these studies have utilised practical hardware, they have thus far not achieved close similarity to the practical environment prevailing within the modern engine combustors at conditions of near-full power operation. Typically, the maximum operating air pressure and temperature values are currently around 40 bar and 900K- yielding an air density of around 16kg/m³. The maximum fuel flows lie between around 100 to 150g/s depending upon the number of fuel injectors in a given engine.

A special feature of the author's work on practical injector geometries has been to maintain as close an operational similarity to the real environment as pragmatic considerations would permit. The initial effort was directed towards visualising the near-nozzle spray cone angle and trajectory using practical injectors in the presence of correctly replicated combustor head air flow features such as the dome air swirler, heat shield assembly etc. [SP 13]. The coupling between the spray emerging from the nozzle⁴ and the major aerodynamic features within the primary zone had, by and large, been ignored in most of the earlier studies. Spray dispersion is a momentum-dominated phenomenon and it is important, therefore, to include all major contributors to this process. This investigation featured a wide range of operating conditions ($\sim 14.5 \text{ kg/m}^3$ air density and 95g/s kerosene flow). A combination of high-intensity spark photography, high-speed cine photography and video imaging was used to capture the instantaneous and dynamic aspects of spray placement. Sprays of such opacity had not been explored before and some of the images, in fact, did not reveal much detail from within the core regions. Nevertheless, the study advanced our knowledge concerning the isothermal behaviour of practical sprays under near-full power operating conditions. Airblast spray trajectory in near-nozzle regions was observed to be significantly influenced by simultaneous changes in ambient air pressure and fuel flow rates.

The author's investigations into the detailed structure of practical sprays using the PDI technique are reported in SP 17, 20 and 22. A first generation instrument was utilised in the initial study, SP 17, and it permitted exploration of spray characteristics up to a maximum of 25g/s kerosene flow rate at an ambient air pressure of 12 bar. Whilst this was clearly inadequate in relation to the typical full-power operating envelope, it nevertheless represented an encouraging and significant advance in our understanding of the structure of practical sprays in a hitherto unexplored environment. Subsequent studies by the author, SP 20 and 22, were aimed at extending the earlier work by embracing more realistic levels of fuel throughput at high ambient air pressures using an upgraded PDI instrument. In addition, the technique of laser sheet imaging, LSI, was also utilised to visualise overview patterns of spray shape, size and dispersion. These studies afforded unique insights into the detailed isothermal structure of practical

airblast sprays at near-full power engine conditions of 75g/s kerosene flow rate and 12 bar air pressure ($= 14.5\text{kg/m}^3$ air density). Moreover, these measurements were ~~4~~ obtained at a distance of 45mm from the injector exit and are of particular relevance from an engineer's viewpoint because they relate to the near-nozzle zone where combustion is initiated and sustained. The effect of operating air pressures and fuel flows upon overall spray mean drop size, drop velocity and size distributions, initial cone angle and spray trajectory were quantified, for the first time, for practical airblast sprays.

These recent studies have revealed some major differences between the behaviour of earlier laboratory-scale research [SP 2] and that of the practical-scale engine airblast fuel injectors [SP 20, 22] – notably the effect of operating air pressure and fuel flow changes on the overall spray SMD and near-nozzle spray trajectory:

- The value of the exponent, n , in the relationship, $\text{SMD} \propto \rho_a^n$, was observed under constant nozzle AFR and air pressure drop conditions to be -0.05 and -0.45 for the practical and the lab-scale injector studies respectively. The primary distinction between the two generic designs explored related to the implicitly different rates of shear invoked in the bulk sheet disintegration process – instantaneous, highly turbulent (i.e. 'prompt') and slow, classical wavy respectively. This behavioural distinction has become apparent only as a result of the author's high ambient air pressure work. Of course, a high-shear design does not necessarily guarantee high rates of shear. For example, because air velocities are low during engine start-up and low power operation, low-shear rates prevail regardless of the atomizer design. This implies that under some engine operating conditions a low-shear mechanism could be dominant, while under other conditions a high-shear mechanism could assume overriding importance.
- Under conditions of constant injector AFR and air pressure drop, the initial spray trajectory in the practical-scale research was influenced appreciably for up to two pre-filmer diameters from the nozzle exit by variations in ambient air pressure. The LSI technique, utilised in SP 20 and 22, gave spray images of vastly superior quality and in consequence, the interpretation of spray trajectory behaviour was

substantially more robust relative to that possible in the earlier study, especially under the most demanding near-full power conditions [SP 13]. This finding was contrary to lab-scale experience based conventional wisdom, which implied the initial spray trajectory to be dependent solely upon the prevailing aerodynamics [1]. It is worth recalling that the lab-scale research featured low-fuel-momentum levels, whereas the practical-scale work was conducted at significantly greater levels of fuel momentum. Clearly, increases in fuel momentum are most likely to be reflected in changes in spray trajectory in regions immediately downstream of the nozzle exit. At distances of about two pre-filmer diameters and beyond, the practical spray trajectory behaviour is akin to that of the lab-scale nozzles i.e. dominated by the prevailing aerodynamics.

The recent research features an unparalleled combination of high air densities and high fuel flows, and thus represents a significant advance in our understanding regarding the isothermal behaviour of practical sprays at near-full power conditions of modern, high performance engine combustors.

3. ENABLING TECHNOLOGIES

The generation of a spray with properties that are commensurate with a given set of combustor performance goals inevitably requires appropriate injector design and trustworthy measurement capabilities. The author's contribution to the closely-coupled enabling technology themes of nozzle design and spray diagnostics is outlined in the following sections.

3.1 Nozzle Design

The primary motivation for nozzle design studies has been the desire to achieve necessary spray performance with a minimum of cost and complexity. In an environment where fine, well-mixed sprays produced by pre-filming airblast atomizers were seen as highly desirable, exploration of alternative simpler airblast nozzle geometries capable of yielding comparable performance was deemed worthwhile. The pre-filming airblast concept requires the generation of a thin, continuous, annular film that is subsequently 'sandwiched' by accelerating, high-velocity air on both sides – thus introducing appreciable design complexity. A much simpler alternative geometry explored by the author dispensed with pre-filming and, utilised 'in-flight' disintegration of multiple, plain liquid jets in a single, high velocity air stream instead [SP 1, 3]. The outcome of these early investigations, which included high ambient air pressures, was encouraging as they revealed the spray performance of this relatively immature concept to be broadly comparable to that of the pre-filming counterpart, especially when operating on lower viscosity fuels. This led to a sustained programme of research on the plain-jet airblast atomizer aimed specifically at its optimisation by exploring the effect of key design variables upon spray performance under atmospheric pressure conditions [SP 4 to 7, 10, 12]. Attention was devoted to both liquid and air flow passage geometry variables in order to identify the conditions most conducive to realising effective interaction between the two fluid streams vis-à-vis spray drop size, cone angle and penetration performance. This plain-jet work revealed the relationship $SMD \propto d_0^{0.5}$, where d_0 is the characteristic diameter of the injection orifice, in contrast to that for the

contemporary thin sheet type, namely $SMD \propto D_p^{0.43}$ [34], where D_p is the characteristic diameter of the pre-filmer lip for the thin sheet design. It was also found that the atomization performance could be improved still further, especially at lower airstream velocities, by utilising the upstream liquid injection configuration [SP10]. In essence, the plain-jet concept was deemed to offer broadly comparable spray quality trends, especially on lower viscosity fuels, relative to the pre-filming type but without the added complexity.

This concept has been adopted in some large industrial gas turbine engines as a part of low-emission, lean pre-mixed, pre-vaporised combustion systems. For example, Siemens AG has incorporated it into a range of gas turbine engines (models V94.2/3, V84.2/3 and V64.3) with considerable success from the standpoint of satisfactory combustion – emissions performance [44-46]. More recently, both United Technologies Research Centre and Parker Hannifin Corporation of USA have explored this plain-jet concept as a means of delivering fuel onto a conventional pre-filming surface that is swept by swirling, ‘sandwiching’ air flows [4, 42, 47]. The motivation behind Parker Hannifin’s interest in this hybrid configuration is the desire to achieve superior thermal management capability by shielding the fuel from high temperature, high-velocity air streams that are characteristic of earlier designs [4]. Furthermore, other design schemes featuring multiple, plain-jets as a means of delivering liquid fuel onto a pre-filming surface are also being explored in lean, pre-mixed, pre-vaporised research configurations under study for aero engines with European Community support. Clearly the knowledge database generated as a result of the author’s earlier research on this concept is helping to guide and underpin the more recent efforts to improve fuel injector design.

3.2 Spray Diagnostics

A major impediment with regard to the attainment of satisfactory fuel-air mixture preparation has been the non-availability of appropriate diagnostic tools for probing the harsh practical environments within which fuel injector has to operate. In consequence, the traditional practice has been to conduct experimental simulations in an easily probed

ambient pressure laboratory environment, followed by protracted and expensive 'cut and try' optimisation and demonstration procedures on engine standard fuel injector/combustor hardware at near full-scale conditions. The advent of PDI and Mie-Fluorescence based laser sheet imaging, LSI, techniques represent two of the most promising characterisation tools of relevance to spray research [48]. Most new techniques yield trustworthy data in simplified, lab-scale experiments. Their true capabilities and limitations in demanding situations more representative of maximum power operation of modern gas turbine combustors, however, are generally not known at the outset. The main thrust of the author's spray diagnostic effort has been directed towards:

- Developing and applying the LSI technique to visualise spray and droplet processes in near-nozzle regions of high throughput, dense sprays under high ambient air pressure conditions.
- To apply the commercial PDI instrument to practical sprays at near-full power conditions in order to determine the limits of its capabilities for measuring the various droplet properties.

Initially the LSI technique was explored under simpler atmospheric conditions in order to optimise it prior to its application to dense, practical sprays. The effect of such key variables as primary magnification, light sheet dimensions (thickness and width) and energy density, imaging media (CCD and conventional wet-film) etc. were investigated using a range of lab-scale spray flow-fields [SP 14, 16, 18, 19]. With appropriate primary magnification it delivered images of high resolution, offering a clearer insight into the details of the liquid break-up mechanism vis-à-vis the capturing of wavy disturbances and the appearance of perforations in the liquid surface prior to the formation of ligaments and droplets [SP 16, 18]. In addition, droplet processes such as dispersion, trajectories, intra-spray re-circulation etc. could also be observed with unparalleled clarity [SP 18]. Equipped with this encouraging lab-scale experience, the technique was applied to dense, practical sprays at near-full power engine conditions. At the severest condition of 75 g/s kerosene flow rate and 14.5 kg/m³ air density the

resolution deteriorated somewhat, but the image quality still remained appreciably superior to that reported elsewhere in the open literature, including this author's previous effort [SP 13]. LSI was principally pursued as an external spray visualisation tool, however it has additionally allowed acquisition of important new insights in respect of the liquid trajectory behaviour inside the pre-filming airblast atomizer investigated [SP 21]. Knowledge of internal liquid trajectory behaviour could be of considerable value to nozzle designers in respect of optimising inner/outer airflow momentum apportioning to realise further improvements in near-nozzle, two-phase spray behaviour. In essence, LSI has turned out to be a very useful and cost-effective tool for acquiring more robust insights into the spray physical structure, dynamics, symmetry, spatial uniformity, cone angle, internal and external fuel trajectories etc. for a range of lab-scale to practical nozzle applications.

A first generation, single velocity component PDI instrument marketed by Aerometrics, Inc., featuring a low powered Helium Neon laser and a counter-based signal processing routine was initially applied to a range of lab-scale sprays under atmospheric pressure conditions [SP 14-16]. Providing the set-up parameters are selected with due care, the PDI technique affords droplet size and velocity data of satisfactory reliability in simple, comparatively dilute atmospheric sprays. The spatially resolved nature of the droplet data was deemed to be very useful in gaining new insights into the extent of point-wise homogeneity present within such sprays. The next phase of the PDI exploration featured experiments on a practical airblast injector under varying air density conditions. The first generation instrument was found to permit drop size and velocity measurements up to a maximum of 25 g/s of kerosene flow rate at 12 bar ambient air pressure ($= 14.5 \text{ kg/m}^3$ air density) at an axial distance of 70 mm from the injector exit [SP 17]. Notwithstanding this encouraging initial outcome, there clearly was a pressing need for further extension in spray characterisation capability to facilitate a better understanding of the detailed structure of practical sprays at higher fuel flows ($\sim 100 \text{ g/s}$) and at shorter axial distances from the nozzle exit ($\sim 50 \text{ mm}$ or less). The near - nozzle region is of special importance because it is the zone in which combustion is initiated and sustained. These early high pressure experiments revealed the signal-to-

noise ratio of the scattered light reaching the detector array deteriorating appreciably with increases in spray density, i.e. with increases in fuel flow and/or reductions in measurement plane distance at the 12 bar air pressure level. Clearly an increase in laser power could be expected to mitigate this problem by raising the incident beam intensity to spray density ratio. In consequence, the PDI instrument was upgraded to incorporate a powerful Argon-Ion laser delivering 1.5W at 514nm wavelength, in contrast to 10mW power at 632nm wavelength delivered by the Helium Neon laser. In addition, the signal processor was also changed from a time-domain counter to a frequency-domain, fast Fourier transform type with its vastly superior capability for detecting Doppler bursts in lower signal-to-noise ratio environments [49]. This second generation PDI instrument enabled the acquisition of droplet property data at kerosene fuel flow rates of up to 75 g/s at the 12 bar ambient air pressure level for an axially downstream distance of 45 mm from the exit of a practical airblast nozzle [SP 20, 22]. Detailed measurements in regions closer to the nozzle exit, for example at 27 mm, were only possible at lower ambient air pressures and on reduced fuel throughputs. This was a reflection of such problems as extinction, particle co-incidence and multiple scattering in optically dense sprays resulting in poor signal-to-noise ratio and abnormal phase shifts. This research has revealed that spatially resolved drop velocity and size distribution information gathered in practical sprays under near-full power air density and fuel flow conditions is generally plausible. On the other hand, the derived quantities of number density and volume flux exhibit absolute values that are often inconsistent and unreliable.

In summary, the ability to reliably determine drop velocity and size distributions, spray dimensions, cone angle and internal – external liquid trajectory behaviour under such challenging conditions constitutes a significant advance in the diagnosis of 'real' sprays under 'near-real' operating conditions, and is currently unparalleled in the open literature.

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5. SUBMITTED PAPERS

Full copies annotated as SP 1 to SP 23

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Atomization of Crude and Residual Fuel Oils

A study is made of the effects that fuel properties have upon the mean droplet size characteristics of three fuel atomizer types that are commonly employed in the gas turbine engine. The fuels tested included kerosine, gas oil, and a heavy residual fuel oil, and each was passed through a pressure swirl jet, a prefilming airblast, and a plain-jet airblast atomizer in turn. Tests were carried out at pressure levels close to ambient and mean drop sizes were determined using a light-scattering technique. Two main points emerge from the results: Firstly, for all atomizers tested, that the existing dropsizes correlations are not sufficiently accurate for use with the high-viscosity residual fuel oils. Secondly, that the fuel dropsizes decreases with the change in atomizer type from plain-jet airblast to prefilming airblast. The difference in performance of the two types of airblast atomizers is most noticeable for the residual fuel oil, particularly so at pressure drop levels of less than around five percent. Use is also made of the many data points collected to derive improved dropsizes correlations which may be used over the whole range of fuels tested.

Introduction

It is well established that fuel atomizer characteristics greatly influence the performance of gas turbine combustors and that the mean droplet size of the fuel, in particular, must be reduced if emissions of such pollutants as smoke are to be limited to acceptable levels. In light of this, numerous atomization studies have been made, particularly of the refined, low-viscosity fuels presently used in gas turbines. Correlations have been obtained relating a dropsizes, termed the Sauter Mean Diameter, to the fuel properties and the atomizer operating conditions. (see for example [1]¹ for pressure swirl atomizers and [2-4] for airblast atomizers). Such correlations, however, have not been tested against the more viscous residual fuel oils that are now of growing interest to the industrial and marine gas turbine users, hence the reason for this study.

Selection of Test Conditions

The fuels selected for testing covered a range from kerosine to residual fuel oil, type BS 2869 Class G, 3500 Second Redwood One. In order to vary the properties within these two extremes, gas oil and a series of gas oil in residual fuel mixtures were also tested, and, in addition, fuel preheating was applied when residual fuel oil was used, as viscosity is known to vary considerably with temperature for these fuels.

The choice of atomizers was limited to those most commonly used in gas turbines, namely the conventional simplex pressure swirl and the prefilming airblast, and tests were also made on a development plain-jet airblast atomizer. The pressure swirl atomizer is more common in old and low-pressure-ratio engines, whereas the prefilming airblast atomizer is to be found on most modern high-pressure-ratio engines. Much interest has grown in recent times, however, in the plain jet atomizer, as it offers, relative to the prefilming type, a much simpler and cheaper system (see Figs. 1 and 2).

The prefilming device of the conventional airblast atomizer spreads the fuel into a thin sheet that is enveloped by high velocity pintle airstream on the inside and shroud airstream on the outside, thereby promoting maximum physical contact between the fuel and airstreams. The plain-jet airblast atomizer merely features a conventional air swirler, just downstream of which fuel issues out of plain circular holes in the form of discrete jets. These jets undergo in-flight disintegration without any prior preparation, such as fuel prefilming.

By the very nature of their design principles, the pressure swirl and the air blast atomizer dimensions are defined in somewhat different ways. The former is characterized in scale by an atomizer flow number, FN , where:

$$FN = \text{Volumetric Flow Rate} / (\text{Fuel Pressure Drop})^{0.5}$$

Flow number, therefore, indicates the size of the discharge orifice through which the fuel flows and the fuel flow rate can be controlled by varying either the fuel pressure or the atomizer flow number. In the case of the airblast atomizers, the scale tends to be defined by the area of the air passages (which for a given atomizer air pressure drop, and air pressure level is a measure of air mass flow rate) and the air-to-fuel mass ratio. The size of atomizers tested was limited by economic considerations.

¹ Numbers in brackets designate References at end of paper.

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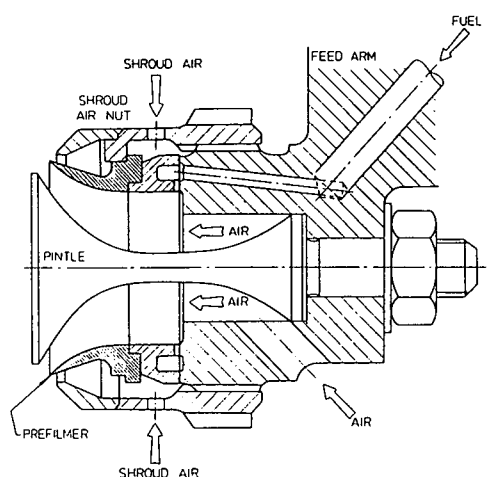


Fig. 1 The prefilming airblast atomizer

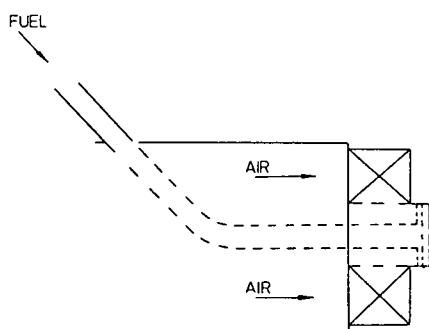


Fig. 2 The plain jet airblast atomizer—outline arrangement

Similar considerations also dictated that the airblast atomizer tests should be carried out at near-ambient air pressure levels, but a wide range of atomizer air-pressure-drop conditions were tested, the range being wider than normally encountered in gas turbine combustors.

The conditions over which the tests were made can be summarized as follows:

Atomizing Media:

- 1) kerosine
- 2) gas oil
- 3) 25 percent residual fuel oil and 75 percent gas oil blend
- 4) 50 percent residual fuel oil and 50 percent gas oil blend (limited tests)
- 5) residual fuel oil with several levels of preheat
- 6) water (limited tests)

Atomizers:

- 1) 3 pressure-swirl, simplex with $FN = 0.25, 0.5$ and 0.8

2) 1 prefilming airblast (Fig. 1 and [5])

3) 1 plain jet airblast (Fig. 2)

Atomizing Air Pressure: near ambient

Air Pressure Drop—Airblast Atomizers: 2 to 11 percent

Experimental Details

Before conducting the main part of the study, the measurement of Sauter Mean Diameters from the fuel atomizers under operating conditions defined above, it was necessary to determine in full the physical properties of all the fuels to be tested. The relative density, surface tension, and kinematic viscosities of each were measured.

The main test facility comprised an air fan, fuel pump and dropsizer measuring equipment. The air mass flow was measured using an orifice plate installed in accordance with BS 1042, and the fuel mass flow rate was measured using precision flowmeters, previously calibrated for each fuel at the appropriate working temperature.

The spray Sauter Mean Diameters were measured using the well-established laser light-scattering technique, an extension of that developed by Dobbins, Crocco and Glassman [6]. The method is based upon the forward diffractive scattering of a parallel, monochromatic beam of light as it passes through the test spray. Fig. 3 shows the details of the optical system for spray mean dropsizer measurement, and its principles and mode of operation are described in [4, 6, 7]. Apart from the rapidity with which data can be obtained, this technique has the advantage that it does not disturb the spray pattern as is the case with all mechanical devices. Recent improvements in the light source as well as optics has enabled spray SMDs of around 20 microns to be measured accurately.

Results

Fuel Characterization. Many tests were made to determine the physical properties of the test fuels, and the results are given in Table 1 and Figs. 4 and 5. The latter figure highlights the variation of property with fuel mixture strength, and special note should be made of nonlinearity of the viscosity-blend relationship. Detailed characterisation of residual fuel oil-gas oil blends is outlined in [8].

The Pressure Swirl Atomizer. The measured atomization performance of a 0.8 flow number pressure swirl atomizer is illustrated in Fig. 6, and the marked increase in spray SMD with deteriorating fuel quality is clearly brought out. A similar trend is also observed on the 0.25 and 0.5 flow number atomizers. The effect of different atomizer flow numbers on a given atomizing medium is shown in Fig. 7 for the low-viscosity kerosine fuel while Fig. 8 depicts the same information for the high-viscosity low-grade residual fuel oil. These figures confirm the already well-established facts that the spray SMD performance, for a constant atomizer fuel pressure drop or alternatively for a constant atomizer fuel mass flow, improves with reducing atomizer flow number. The beneficial influence exerted by the increased level of residual fuel oil preheat is outlined in Fig. 9.

The Prefilming Airblast Atomizer. The SMD performance of the prefilming airblast atomizer when operating with different fuels and varying levels of atomizer air pressure drop is illustrated in Figs. 10 and 11. The advantages in terms of improved atomization perfor-

Nomenclature

SMD = Sauter Mean Diameter, m

V = velocity, m/s

W = mass flow rate, kg/s

t = liquid film thickness, m

D = diameter of plain jet fuel orifice, m

ΔP = atomizer pressure drop, N/m^2

P = upstream pressure, N/m^2

AFR = air to fuel mass ratio

ρ = density, kg/m^3

σ = surface tension, N/m

η = absolute viscosity, NS/m^2

ν = kinematic viscosity, m^2/s

FN = atomizer flow number,

$\frac{\text{volumetric flow rate in Imperial gals/hr}}{\sqrt{\text{fuel pressure drop in PSID}}}$

(NOTE: 1 PSID $\equiv 6.89 \times 10^3 N/m^2$;

Imperial Gals/hr $\equiv 1.2628 \times 10^{-6} m^3/s$)

Subscripts

a = air

l = liquid

r = relative

f = fuel

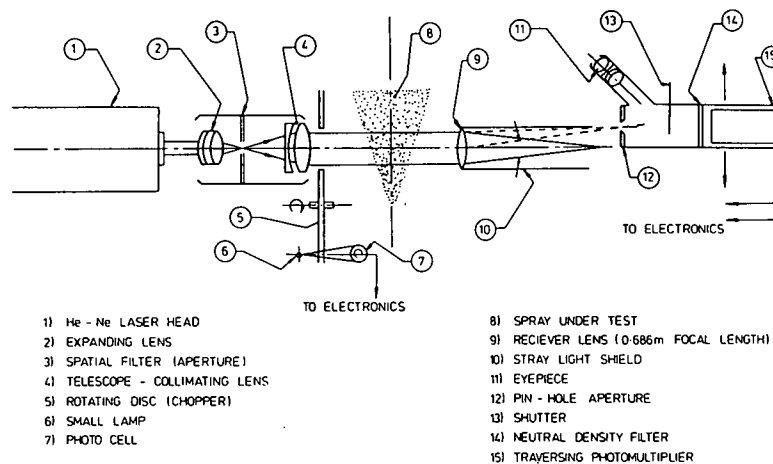


Fig. 3 The optical bench in diagrammatic form

TABLE 1 Physical Properties of Test Fuels

Fuel Property	Keros- ine	Gas Oil	25% RFO 75% GO	50% RFO 50% GO	100% RFO
Density ρ_f in Kg/m ³ at 15°C	784	853	870	910	966
Surface Tension σ_f in N/m at 20°C	0.0277	0.0299	0.0307	0.0331	0.0353
Absolute Viscosity η_f in Ns/m ² at 15°C	0.0013	0.0051	0.0120	0.0592	—
75°C	—	—	—	—	0.0860
85°C	—	—	—	—	0.0534
100°C	—	—	—	—	0.0300

P_B - DENOTES PROPERTY VALUE FOR BLEND
 P_G - DENOTES PROPERTY VALUE FOR GAS OIL
 P_R - DENOTES PROPERTY VALUE FOR RESIDUAL FUEL OIL

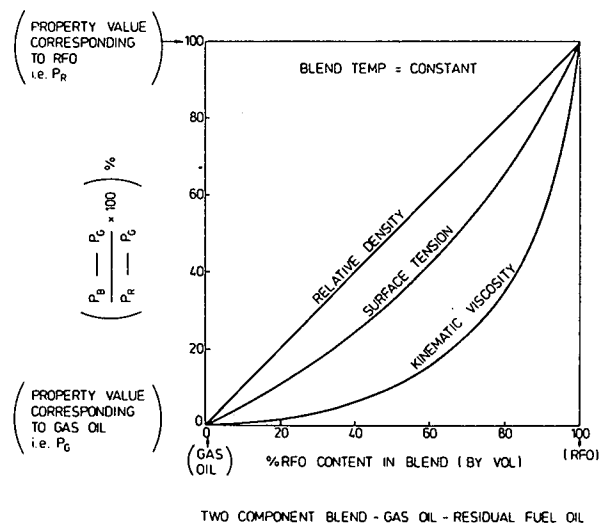


Fig. 5 Nature of property variation as a function of blend mix

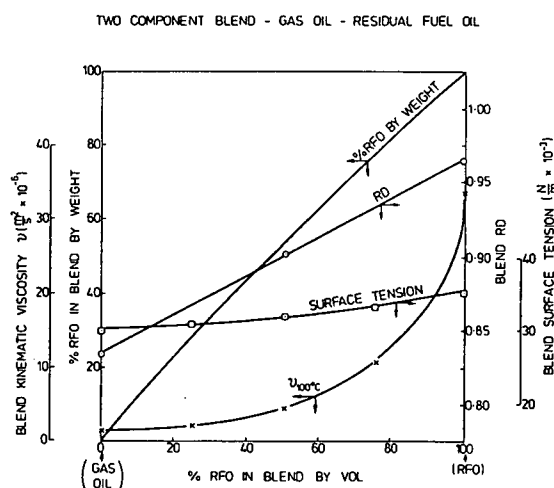


Fig. 4 Fuel characterisation—summary

mance for increasing levels of atomizer air pressure drop (i.e., atomizing airstream velocity) and increasing levels of atomizer air/fuel ratio are clearly illustrated by these figures. Also apparent from the same figures is the deleterious influence exerted by the degrading fuel quality on atomization quality.

The performance with residual fuel oil is illustrated in Fig. 12 for an atomizer air/fuel ratio of 2, and in Fig. 13 for an air/fuel ratio of 4.

As is to be expected, the atomization quality improves with increasing degree of preheat due principally to the reduction in viscosity.

The experimental data outlined in Figs. 10–13 is confined to the all-important air-to-fuel ratio range of 2 to 4 (see [2]), although in fact a much wider range (1 to 8) was investigated. Furthermore, since the tests were conducted under atmospheric pressure conditions, the atomizer air pressure drop and the atomizing air velocity were correlated by using the Bernoulli's equation for incompressible flow.

The Plain Jet Airblast Atomizer. SMD characteristics of the plain jet airblast atomizer when spraying different fuels with varying levels of atomizer air pressure drop under atmospheric pressure conditions are shown in Figs. 14 and 15. Not surprisingly, the plain jet airblast atomizer exhibits somewhat similar performance trends as were observed in the case of the prefilming airblast atomizer, i.e., a reduction in SMD with increasing levels of atomizer air pressure drop as well as with increasing atomizer air/fuel ratio, and an increase in SMD with a degradation in fuel quality. As in the case of prefilming airblast atomizer, the experimental data was obtained over a much wider range of air-to-fuel ratio (1 to 8) although in fact it is only presented for the 2 to 4 range.

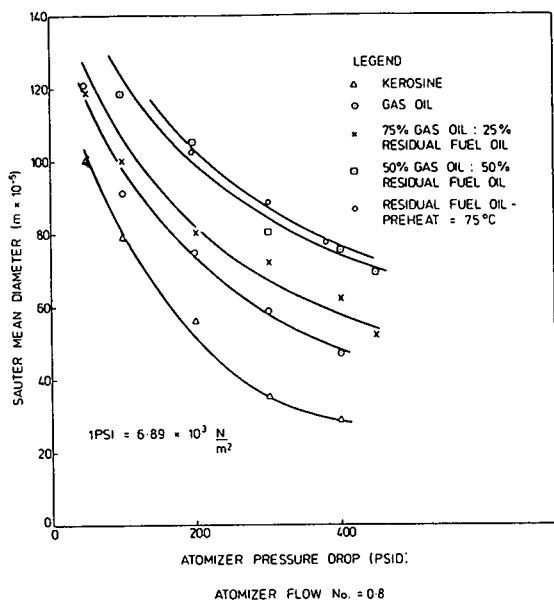


Fig. 6 Spray mean dropsize characteristics of Delavan pressure swirl atomizer when operating on different fuels

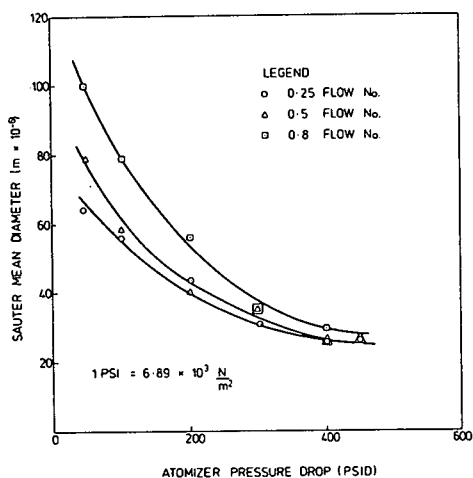


Fig. 7 Effect of atomizer flow number on spray mean dropsize characteristics of Delavan pressure swirl atomizer when operating on kerosine

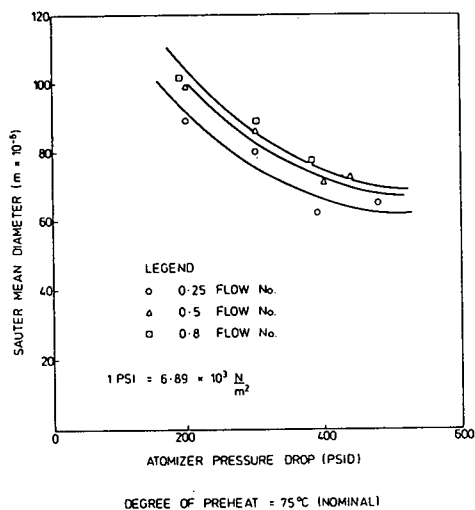


Fig. 8 Effect of atomizer flow number on spray mean dropsize characteristics of Delavan pressure swirl atomizer when operating on residual fuel oil

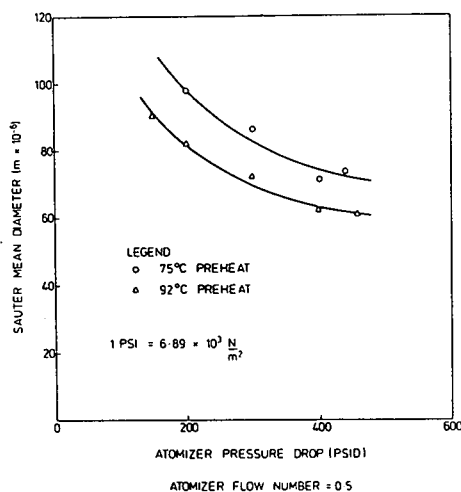


Fig. 9 Influence of preheat on spray mean dropsize characteristics of Delavan pressure swirl atomizer when operating on residual fuel oil

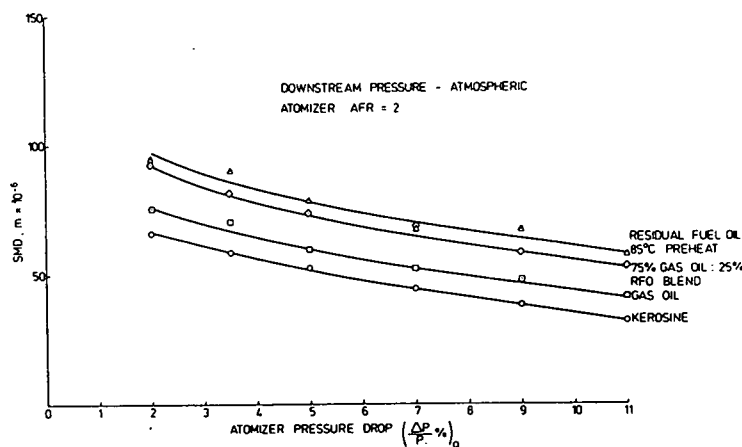


Fig. 10 Prefilming airblast atomizer performance when operating on different fuels—atomizer AFR = 2.

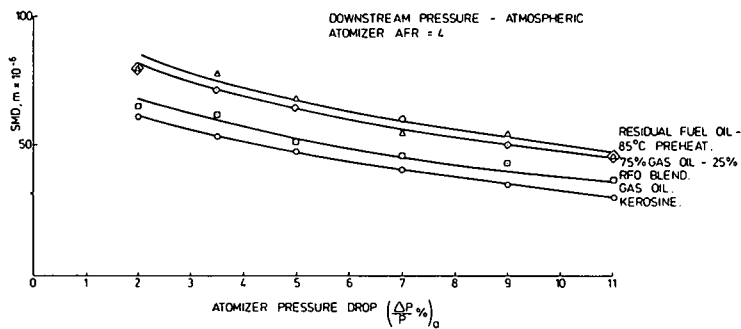


Fig. 11 Prefilming airblast atomizer performance when operating on different fuels—atomizer $AFR = 4$

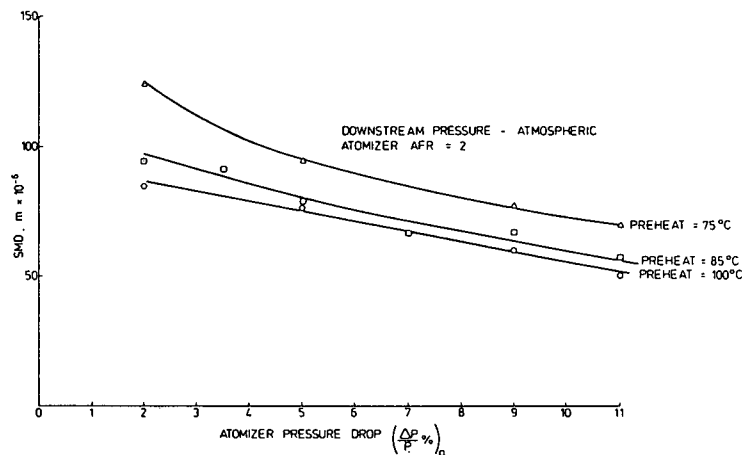


Fig. 12 Influence of varying degrees of residual fuel oil preheat on prefilming airblast atomizer performance—atomizer $AFR = 2$

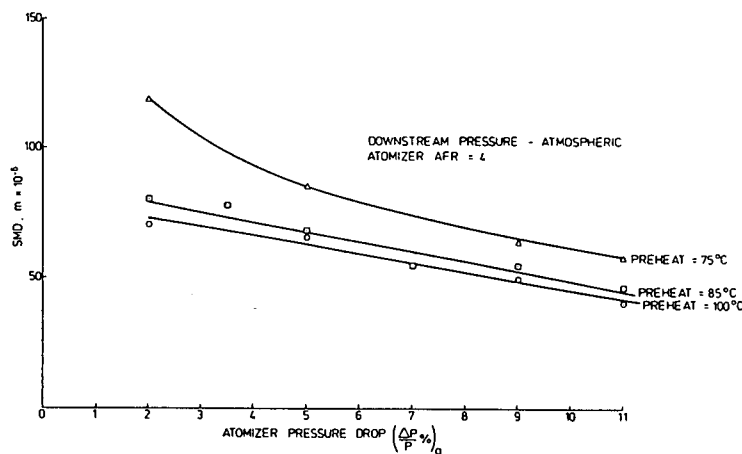


Fig. 13 Influence of varying degrees of residual fuel oil preheat on prefilming airblast atomizer performance—atomizer $AFR = 4$

Comparison of Airblast Atomizers. Figs. 16 and 17 are intended to provide performance comparisons between the prefilming airblast and the plain jet airblast atomizers for kerosine and residual fuel oils. These figures are of direct relevance to atomizer design and, under atmospheric pressure conditions, reveal that:

1 For low-viscosity kerosine fuel the plain jet airblast atomizer has SMD performance comparable to that of the prefilming airblast atomizer at pressure drop values in excess of four percent. However, as the atomizer pressure drop falls below this value, the superiority

of the prefilming airblast atomizer over the plain jet airblast atomizer becomes increasingly apparent.

2 When operating with the high-viscosity residual fuel oil, atomization performance of the prefilming airblast atomizer throughout the air pressure drop range investigated is significantly superior to that of the plain jet airblast atomizer. The superiority becomes increasingly marked as the atomizer pressure drop falls below about five percent.

It should be noted that the former comment agrees with the con-

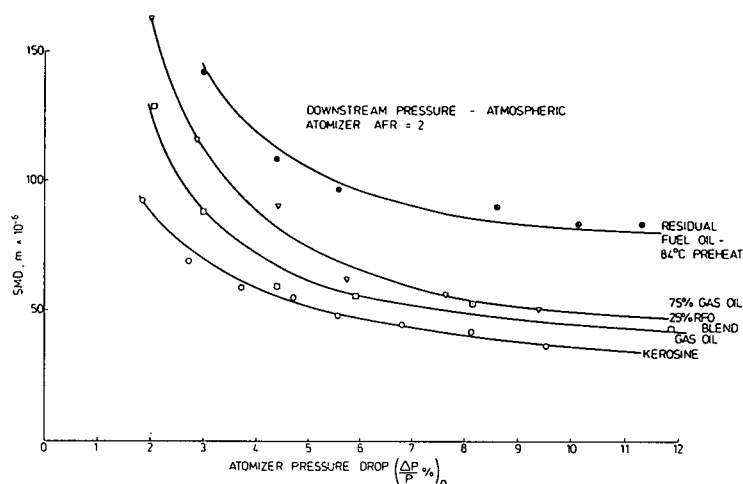


Fig. 14 Plain jet airblast atomizer characteristics when operating on different fuels—atomizer AFR = 2

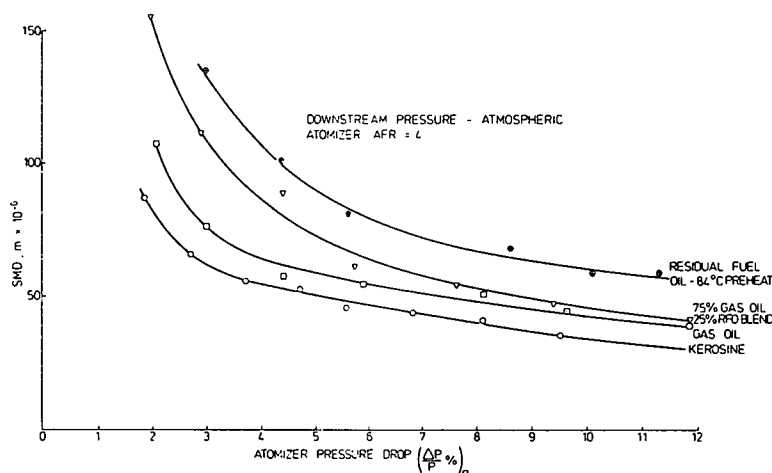


Fig. 15 Plain jet airblast atomizer characteristics when operating on different fuels—atomizer AFR = 4

clusions reported in [3] and [4].

Analysis of Results

The Pressure Swirl Atomizer. Experimental SMD data from the simplex pressure swirl atomizer of flow number 0.8 are compared in Fig. 18, against the predictions of SMD correlation outlined in [1]. The disparity in experimental and predicted values is quite noticeable for the high-viscosity spray media. By plotting $\log(SMD)$ versus $\log(\text{viscosity})$, $\log(SMD)$ versus $\log(\text{atomizer pressure drop})$, etc., the exponents for the different SMD controlling variables in a power law relationship were deduced from the experimental data to yield the following correlation:

$$SMD = 4.4\nu^{0.16}\sigma^{0.6}W_f^{0.22}\Delta P_f^{-0.43} \dots \quad (1)$$

Equation 1 is found to be capable of satisfactorily correlating the entire pressure swirl atomizer experimental data collected in this study (see Fig. 19).

The Prefilming Airblast Atomizer. The prefilming airblast atomization study conducted by Rizkalla and Lefebvre [2] led to the development of the following dimensionless equation:

$$SMD/t = A(\sigma_{\ell}\rho_{\ell}/t)^{0.5}(V_a\rho_a)^{-1}(1 + 1/AFR) + B(\eta_{\ell}^2/\sigma_{\ell}\rho_a)^{0.425}(1 + 1/AFR)^2 \dots \quad (2)$$

where A and B are constants.

However, as no measurements were made of the liquid film thickness at the prefilming lip, the dimensionless constants A and B of equation (2) could not be evaluated. By neglecting liquid film thickness, and thereby sacrificing its dimensionless form, the following equation was derived for the particular prefilming airblast atomizer under their study:

$$SMD = 6.5 \cdot 10^{-4}(\sigma_{\ell}\rho_{\ell})^{0.5}(V_a\rho_a)^{-1}(1 + 1/AFR) + 1.2 \cdot 10^{-4}(\eta_{\ell}^2/\sigma_{\ell}\rho_a)^{0.425}(1 + 1/AFR)^2 \dots \quad (3)$$

Equation (3) was considered (in [2]) to be valid in basic form for any prefilming type of airblast atomizer. It was argued that the constants $6.5 \cdot 10^{-4}$ and $1.2 \cdot 10^{-4}$ of equation (3) need only be replaced by new constants for any new atomizer and that their values could be evaluated from a few experimental measurements, and the resulting equation may then be used to estimate SMD values for other atomizing media and for other operating conditions. This hypothesis was tested against the data obtained from the low-viscosity fuels (kerosine, gas oil, and a 25 percent residual fuel oil/75 percent gas oil blend). Fig. 20 shows that the degree of correlation is very satisfactory when $A = 9.0 \cdot 10^{-4}$ and $B = 0.75 \cdot 10^{-4}$.

However, as the viscosity of the sprayed medium is increased, an increasing measure of disparity is observed between the experimental SMD values and those predicted using the above new A and B values (see Fig. 21). Consequently, attempts were made to obtain a correla-

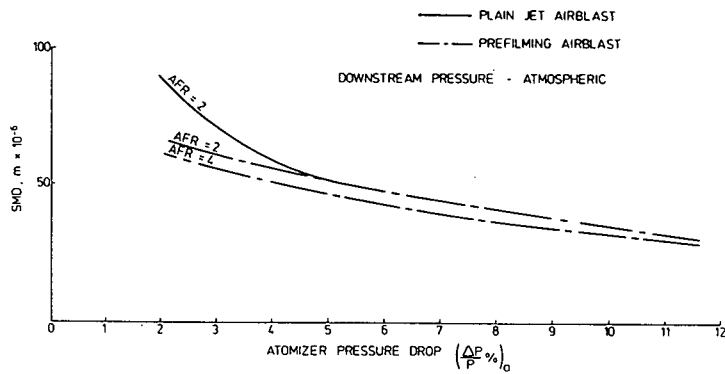


Fig. 16 Performance comparison of airblast atomizers when operating on kerosine

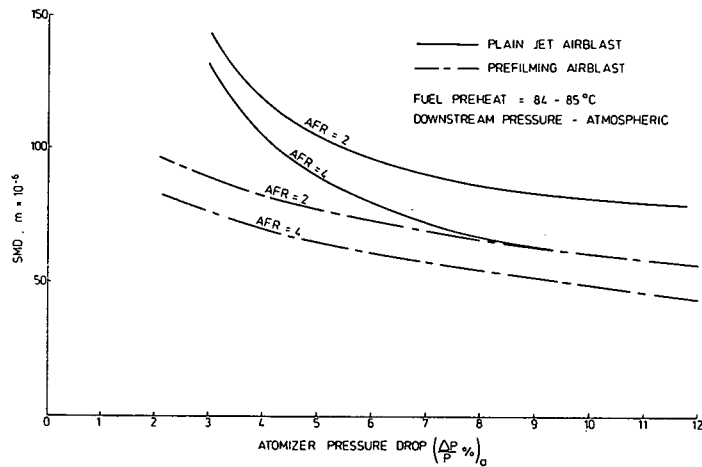


Fig. 17 Performance comparison of airblast atomizers when operating on preheated residual fuel oil

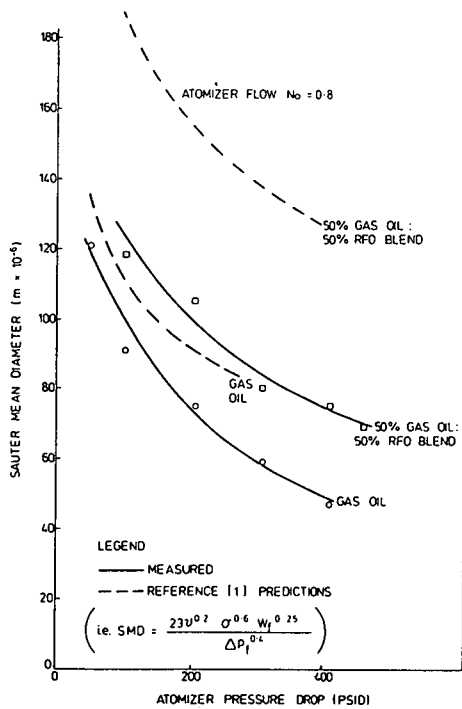


Fig. 18 Comparison of predicted (1) and measured spray mean dropsizes characteristics of Delavan pressure swirl atomizer

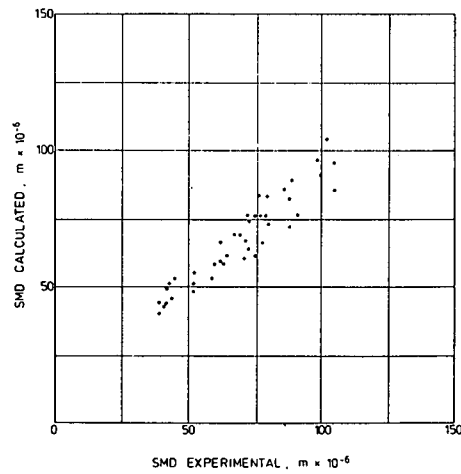


Fig. 19 Comparison of calculated and experimental values of SMD (Delavan pressure swirl atomizer data)

tion that would give better agreement with all the low and high-viscosity fuel data. But since some major parameters such as air density and surface tension had been maintained essentially constant during these tests, such attempts ab initio were somewhat restricted. However, it was discovered that by retaining the basic nature (and thereby the rationale) of equation (3) and modifying the exponents of the

nondimensional $(1 + 1/AFR)$ term only, the entire experimental data could be satisfactorily correlated by the relationship:

$$SMD = [1.0 \cdot 10^{-3}(\sigma_\ell \rho_\ell)^{0.5}(V_a \rho_a)^{-1} + 0.6 \cdot 10^{-4}(\eta_\ell^2/\sigma_\ell \rho_a)^{0.425}] \times (1 + 1/AFR)^{0.5} \dots (4)$$

The level of correlation obtained is shown in Fig. 22 and is obtained from data covering the following extended range of conditions:

Fuel Viscosity	—	0.001 to 0.086 Ns/m ²
Air Velocity	—	55 to 135 m/s
Air-Fuel Ratio	—	1 to 8

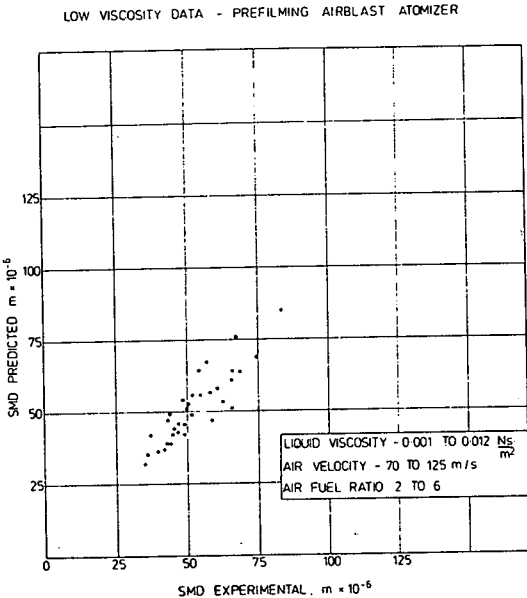


Fig. 20 Comparison of experimental values with predictions in [2] when $A = 9.0 \cdot 10^{-4}$, $B = 0.75 \cdot 10^{-4}$ —low viscosity data

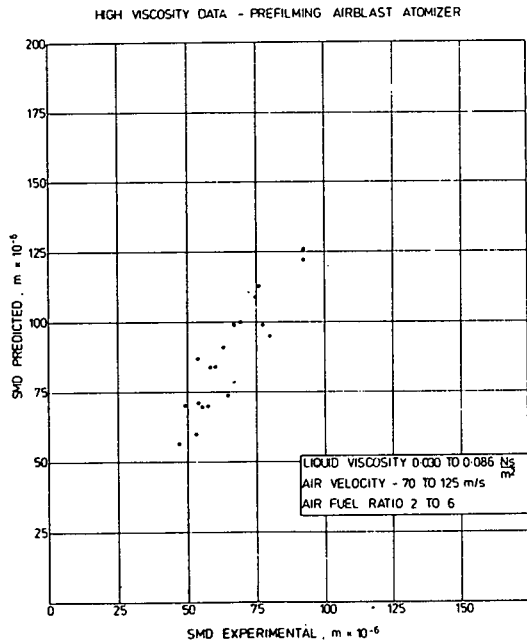


Fig. 21 Comparison of experimental values with predictions in [2] when $A = 9.0 \cdot 10^{-4}$, $B = 0.75 \cdot 10^{-4}$ —high viscosity data

In practical terms, the influence of this change is to diminish noticeably the predicted effect of the second (viscosity) term in the original SMD equation and thereby redress the relative contribution of the two terms.

The Plain Jet Airblast Atomizer. A recent airblast atomization study of a single plain jet type (reported in [3] and [4]) led to the development of the following SMD correlation:

$$SMD = [0.95(\sigma_\ell W_\ell)^{0.35}(V_r \rho_\ell^{0.35} \rho_a^{0.35})^{-1} + 0.127 \eta_\ell (D/\rho_\ell \sigma_\ell)^{0.5}] (1 + 1/AFR)^{1.75} \dots (5)$$

This correlation was also found to be inadequate for the fuels tested in this study. Attempts were made, primarily by judicious trial and error due to the scarcity of data, to obtain an improved correlation of a nature similar to equation (5) above. The values of D , the diameter of the fuel orifice, and ρ_a , the air density were not varied here, and hence it is recognized that further work will be required before reliable correlation can be obtained.

It was found, however, that a satisfactory (but dimensionally inconsistent) correlation could be found by use of the following relationship:

$$SMD = 0.19(\sigma_\ell/\rho_\ell)^{0.35}(V_a \rho_a^{0.35})^{-1}(1 + 1/AFR)^{0.25} + 0.127 \eta_\ell (D/\rho_\ell \sigma_\ell)^{0.5}(1 + 1/AFR) \dots (6)$$

The results obtained by the application of equation (6) are given in Fig. 23.

Conclusions

1 The SMD performance of the pressure swirl atomizers, when spraying in stagnant air at atmospheric pressure, is predicted with a reasonable degree of accuracy by the correlation:

$$SMD = 4.4 \mu^{0.16} \sigma^{0.6} W_f^{0.22} \Delta P_f^{-0.43}$$

for the following range of fuel conditions:

- kinematic viscosity = $1.0 \cdot 10^{-6}$ to $93.0 \cdot 10^{-6}$ m²/s
- surface tension = 0.027 to 0.035 N/m
- pressure drops up to $35 \cdot 10^5$ N/m²

2 Similarly, for the prefilming airblast atomizer studied in the present investigation:

$$SMD = [1.0 \cdot 10^{-3}(\sigma_\ell \rho_\ell)^{0.5}(V_a \rho_a)^{-1} + 0.6 \cdot 10^{-4}(\eta_\ell^2/\rho_a \sigma_\ell)^{0.425}] \times (1 + 1/AFR)^{0.5}$$

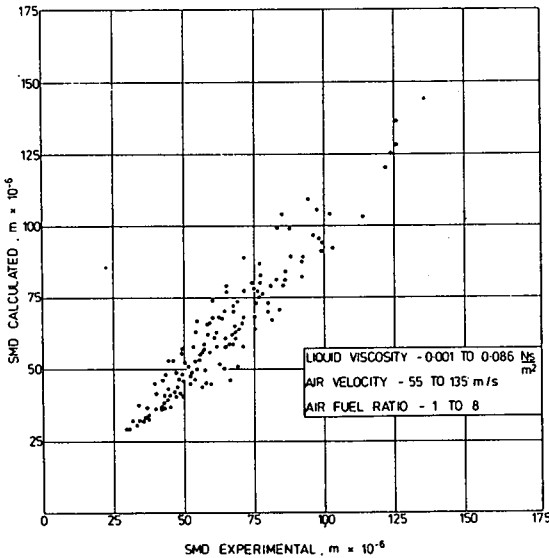


Fig. 22 Comparison of calculated and experimental values of SMD using revised correlation for prefilming airblast atomization

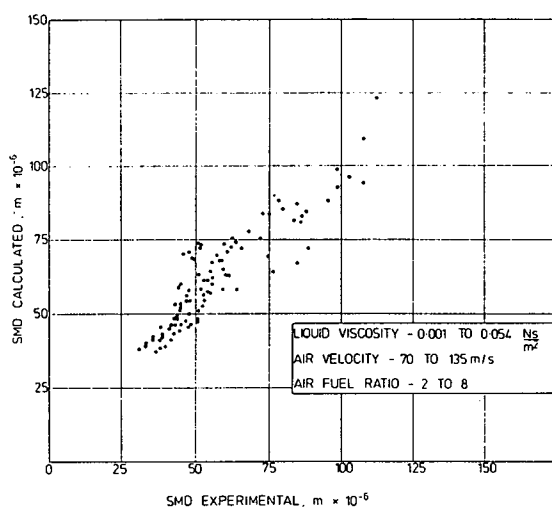


Fig. 23 Comparison of calculated and experimental values of SMD for plain jet airblast atomizer

over the extended range:

fuel viscosity	= 0.001 to 0.086 Ns/m ²
air velocity	= 55 to 135 m/s
atomizer air/fuel ratio	= 1 to 8

3 The contribution of the absolute viscosity term in the above equation changes from one of insignificance for the low-viscosity kerosine fuel to that of increasing significance for the high-viscosity residual fuel oil.

4 Over the following range of operating conditions:

liquid density	= 784 to 1000 kg/m ³
liquid surface tension	= 0.027 to 0.074 N/m
liquid viscosity	= 0.001 to 0.0534 Ns/m ²
atomizer air/fuel ratio	= 2 to 8
air velocity	= 70 to 135 m/s

the spray mean dropsizes obtained for the plain jet airblast atomizer in the present investigation are predicted with reasonable accuracy by the correlation:

$$SMD = 0.19(\sigma_L/\rho_L)^{0.35}(V_a\rho_a)^{0.35}(1 + 1/AFR)^{0.25} + 0.127\eta_L(D/\sigma_L\rho_L)^{0.5}(1 + 1/AFR)$$

5 For low-viscosity kerosine fuel, the plain jet airblast atomizer has an SMD performance under atmospheric pressure conditions comparable to that of the prefilming airblast atomizer when the air pressure drop exceeds 4 percent. However, the superiority of the prefilming airblast atomizer becomes increasingly marked as the atomizer pressure drop falls below this value.

6 When operating on low-grade high-viscosity residual fuel oil, the SMD performance of the prefilming airblast atomizer, throughout the atmospheric air pressure drop range investigated, is significantly superior to that of the plain jet airblast atomizer. The prefilming airblast atomizer's superiority becomes increasingly marked as the atomizer pressure drop falls below about 5 percent.

Acknowledgments

The author wishes to thank the Wolfson Foundation for sponsoring the residual fuel oil gas turbine combustion study of which this forms a part, and the British Petroleum Company Ltd. for supplying the residual fuel oil. Thanks are also due to the staff of the School of Mechanical Engineering, in particular to Prof. R. S. Fletcher, Dr. N. Rizk, and Mr. R. Kennewell, for their invaluable encouragement and assistance.

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Airblast Atomization of Alternative Liquid Petroleum Fuels under High Pressure Conditions

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A study has been conducted of the effects that fuel and air properties have upon the mean droplet size characteristics of a pre-filming airblast atomizer of the type commonly employed in the gas turbine engine. The fuels tested included kerosine, gas oil and two blends of gas oil in residual fuel oil. The tests were carried out over a wide range of air pressures (about 1 to 13 atmospheres), fuel viscosities (about 0.001 to 0.037 Ns/m²) and the spray mean drop sizes were measured using a laser light-scattering technique. The experimental data accumulated in the study is presented in the paper and it is concluded that the spray Sauter Mean Diameter performance of the atomizer studied can be predicted to a reasonable degree of accuracy, over the range of conditions studied, by a relatively simple correlating equation.

Introduction

It is generally accepted that the quality of the future petroleum fuels will deteriorate, requiring the gas turbine to burn increasingly viscous and less volatile, low-grade fuels. In order to minimize the deleterious influence of such a change, there is a real need to focus attention on the details of such combustion processes as spray atomization, evaporation, ignition etc. Although it is possible from a theoretical standpoint to compensate for the degradation in fuel viscosity and volatility by improvements in atomization performance, the extent of such an improvement in a practical situation may be either limited in scope or difficult to realize. Consequently, there is a growing requirement for experimental data aimed at quantifying these effects in gas turbine combustors.

The results of the atomization study under atmospheric pressure conditions, covering a variety of gas turbine type fuel atomizers operating with a wide range of alternative liquid petroleum fuels, were reported in reference [1]. This paper presents the experimental data collected in the course of the airblast atomization study under conditions of high pressure. Although reference [2] outlines some high pressure atomization data, the range of applicability as regards ambient air pressure and test fuel viscosity levels is very limited—i.e., data pertaining to low-viscosity liquids such as kerosine/water for pressures up to about 8.5 atmospheres. Further, there is no high pressure data whatsoever in the study outlined in reference [3]. Clearly, therefore, more information is required in order to cover the range of operating air pressures/fuel viscosities that are of relevance to the gas turbine, particularly in its industrial and marine applications.

Selection of Test Conditions

The fuels selected for this study comprised kerosine, gas oil and two blends of gas oil in residual fuel oil, type BS 2869 Class G, 3500 Second Redwood One (860 cSt.). The blends were designated R₂₅ and R₅₅

containing 25 percent and 55 percent residual fuel oil (by volume) respectively, the remainder in each case being gas oil. This enabled test fuel viscosity variation over a wide range, (see Table 1).

The choice of the atomizer type was limited, for this particular phase, to the prefilming type of airblast atomizer—a common feature of most modern high-pressure-ratio gas turbines in view of its superior combustion/pollution performance. Figure 1 shows the atomizer arrangement. The prefilmer spreads the fuel into a thin sheet that is enveloped by high velocity airstreams on both sides—pintle airstream on the inside and shroud airstream on the outside. The object of sandwiching a low velocity sheet of fuel by two high velocity airstreams is to promote maximum physical contact between the fuel and air and thereby set up high rates of shear.

The atomizer operating conditions covered a wide range of air properties as detailed below:

Atomizing air pressure. From about 1 to 13 atmospheres

Atomizing air pressure drop. From about 2 to 11 percent, being wider than that normally encountered in gas turbine combustors

Atomizer air to fuel mass ratio. From about 2 to 8.

Table 1 Physical Properties of Test Fuels

Fuel Property	Kerosine	Gas Oil	25 Percent RFO	55 Percent RFO
			75 Percent GO	45 Percent GO
Density ρ_f in kg/m ³ at 15°C	784	846	874	913
Surface tension σ_f in N/m ³ at 20°C	0.0277	0.0299	0.0307	0.0331
Absolute viscosity η_f in Ns/m ² at 15°C	0.0013	0.0053	0.0149	0.0749
at 25°C	—	0.0040	0.0102	0.0435
at 35°C	—	0.0031	0.0073	0.0275

Contributed by the Gas Turbine Division for publication in the JOURNAL OF ENGINEERING FOR POWER. Manuscript received by the Gas Turbine Division January 28, 1980.

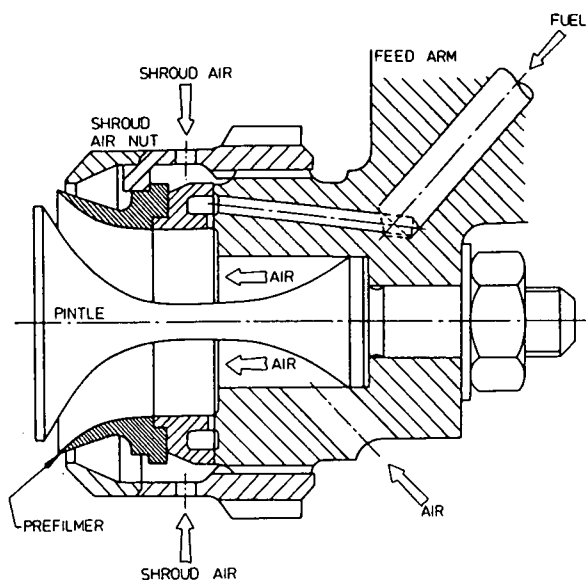


Fig. 1 The prefilming airblast atomizer

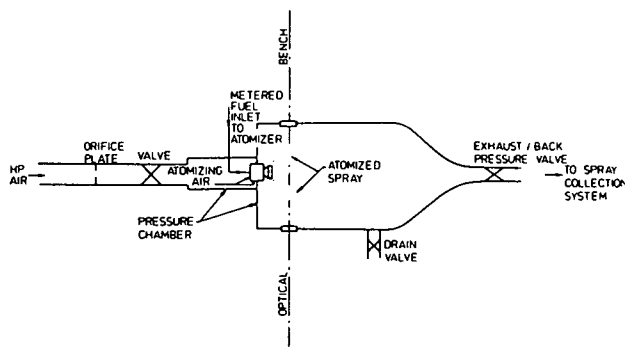


Fig. 2 Outline arrangement of the test installation

Experimental Details

Figure 2 shows the outline arrangement of the test facility. The atomizer was mounted in a pressure chamber connected to the School's high pressure air supply system comprising multistage Howden compressors. The air mass flow rate was measured using an orifice plate fitted with D and D/2 pressure tappings in accordance with BS1042. Fuel mass flow rate was measured using precision flowmeters, previously calibrated for each fuel at the appropriate working temperature.

As in the case of earlier study [1], the spray Sauter Mean Diameters were measured using the well-established laser light-scattering technique, an extension of that developed by Dobbins, et al. [4]. This is based on the principles of forward diffractive scattering of a parallel monochromatic beam of light as it passes through the fuel spray. For more details of the optical bench see references [1, 4, 5]. It is generally believed that spray SMD's down to about 20 μm can be measured reasonably accurately.

The pressure chamber was fitted with optical windows to enable laser beam access for measuring the atomized spray Sauter Mean Diameter under conditions of high pressure.

Nomenclature

SMD = Sauter Mean Diameter, m

V = velocity, m/s

D = diameter of prefilmer, m

$\frac{\Delta P}{P}$ = atomizer air pressure drop, percent

AFR = air to fuel (liquid) mass ratio

ρ = density, kg/m^3

σ = surface tension, N/m

η = absolute viscosity, Ns/m^2

Subscripts

a = air

l = liquid

f = fuel

Results

Fuel Characterization. Many tests were carried out to determine the physical properties of the various fuels and the detailed results are given in Table 1. The mean absolute viscosities, in Ns/m^2 , of the different test fuels at the working temperature for the ensuing atomization results were: kerosine—0.0013, gas oil—0.0058, R_{25} —0.0122 and R_{55} —0.0371.

Atomizer Performance. The effect upon SMD performance of varying the atomizer air to fuel mass ratio (AFR) for a range of ambient air pressures at a constant atomizer air pressure drop is illustrated in Figs. 3 and 4 for low-viscosity kerosine and high-viscosity R_{55} fuels, respectively. Figure 3 indicates that, in the case of kerosine, the atomizer AFR has a bearing on the atomizer SMD performance close to the atmospheric pressure condition only—at higher ambient air pressures there being no significant change in SMD values for an AFR change. As the fuel viscosity increases, the AFR influence upon SMD values begins to become apparent even at higher ambient air pressures. In the case of R_{55} fuel, the AFR effect seems to extend from atmospheric up to around 7 atmospheres, though to a noticeably diminishing degree. In airblast atomizer design, the scale tends to be related to AFR, and therefore due consideration must be given to the interaction of AFR, ambient air pressure and fuel viscosity.

The influence of atomizer air pressure drop, or alternatively air-stream velocity, upon mean drops size performance for various levels of ambient air pressure is depicted in Fig. 5 for kerosine, and in Fig. 6 for high-viscosity fuel R_{55} . Both these figures illustrate clearly the beneficial influence of increased levels of atomizing air velocity upon SMD performance. For atmospheric pressure conditions the atomizer air pressure drop and the atomizing air velocity were correlated by using the Bernoulli's equation for incompressible flow, while for high pressure conditions the calculations were based upon compressible flow.

Also brought out clearly in Figs. 3–6 is the noticeable improvement in atomizer performance as the ambient pressure of the atomizing air increases i.e. the atomizing air density. It should be pointed out here that in the case of 1 atmosphere data, the ambient pressure of 1 atmosphere is that prevailing downstream of the atomizer, making the atomizer upstream pressure a little above 1 atmosphere when taking into account the atomizer air pressure drop. In all other cases, the ambient air pressures quoted are the actual nominal atomizer upstream air pressures.

Figures 7–9 illustrate the effect of fuel quality degradation (essentially fuel viscosity) upon the mean drop size characteristics, for 1, 6.8 and 12.9 atmospheres, respectively. These results are for an atomizer air to fuel ratio of 4, although in fact a much wider range (2 to 8) was investigated.

The improvement in atomization quality as a result of an increase in atomizing air ambient pressure, for the entire range of fuels employed in this study, is illustrated by Figs. 10 and 11 for two typical atomizer air pressure drop levels. It is apparent from these figures that the improvement in drops size performance with an increase in air pressure is more marked for the low-viscosity fuels such as kerosine and gas oil than for the higher-viscosity R_{55} fuel.

Analysis of Results

The data collected from the low-viscosity kerosine fuel tests were systematically evaluated and found to correlate with an equation of the form:

$$\text{SMD} \propto \left(\frac{\sigma_l}{\rho_a V_a^2} \right)^{0.45} \cdot (1 + 1/\text{AFR})^{0.5} \quad (1)$$

ATOMIZER AIR PRESSURE DROP = 3.5 PERCENT (NOMINAL)
 SPRAY MEDIUM - KEROSENE

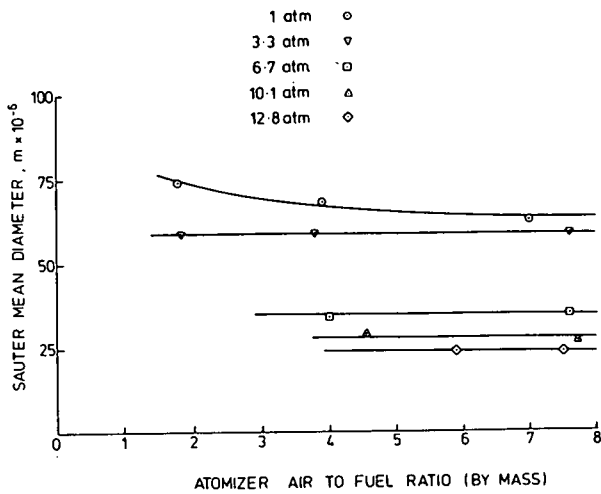


Fig. 3 Atomizer mean droplet performance under varying ambient air upstream pressure and air to fuel ratio (kerosene)

ATOMIZER AIR TO FUEL RATIO = 4
 SPRAY MEDIUM - KEROSENE

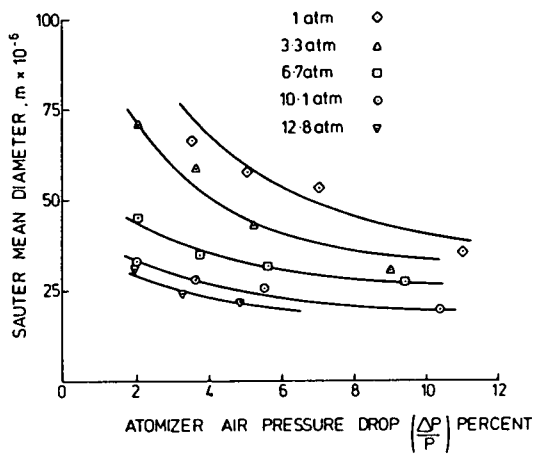


Fig. 5 Influence of varying atomizer air pressure drop and ambient air upstream pressure on spray mean droplet size

Examination of the high-viscosity droplet data reveals that the fuel viscosity apparently exercises an influence somewhat independent of the air properties—namely air velocity and density, thus implying that to the right hand side of the equation (1) above should be added another term taking into account the effect of fuel viscosity upon SMD. As before, a log-log analysis of the high-viscosity data was conducted to yield:

$$\text{SMD} \propto \left(\frac{\sigma_L}{\rho_a V_a^2} \right)^{0.45} \cdot (1 + 1/\text{AFR})^{0.5} + \left(\frac{\eta_L^2}{\rho_L \sigma_L} \right)^{0.375} \cdot (1 + 1/\text{AFR})^{0.8} \quad (2)$$

It is interesting to note that the equation (2) above is not dimensionally consistent but can be made so by introducing the prefilmer diameter D as given below:

$$\text{SMD} = A \left[\left(\frac{\sigma_L}{\rho_a V_a^2} \right)^{0.45} \cdot (D)^{0.55} \cdot (1 + 1/\text{AFR})^{0.5} + B \left(\frac{\eta_L^2}{\rho_L \sigma_L} \right)^{0.375} \cdot (1 + 1/\text{AFR})^{0.8} \right] \quad (3)$$

ATOMIZER AIR PRESSURE DROP = 3.5 PERCENT (NOMINAL)
 SPRAY MEDIUM - R₅₅ BLEND (55% RFO : 45% GO)

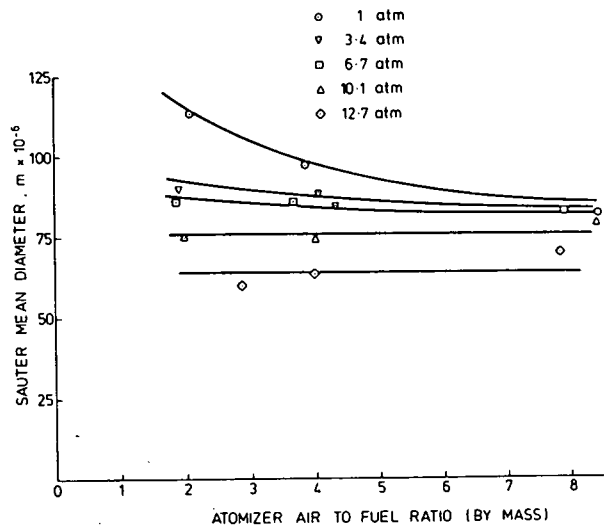


Fig. 4 Atomizer mean droplet performance under varying ambient air upstream pressure and air to fuel ratio (R₅₅ blend)

ATOMIZER AIR TO FUEL RATIO = 4
 SPRAY MEDIUM - R₅₅ BLEND (55% RFO : 45% GO)

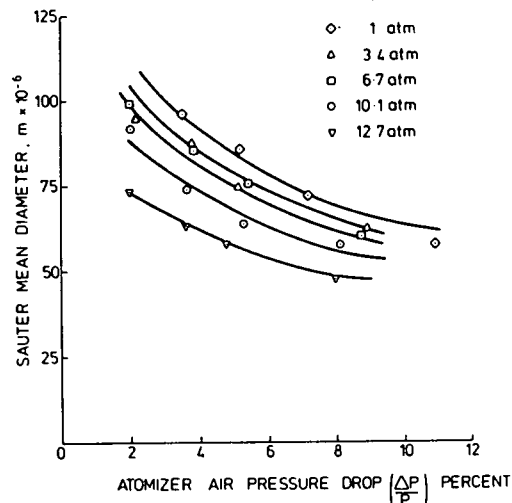


Fig. 6 Influence of varying atomizer air pressure drop and ambient air upstream pressure on spray mean droplet size

$$+ B \left(\frac{\eta_L^2}{\rho_L \sigma_L} \right)^{0.375} \cdot (D)^{0.625} \cdot (1 + 1/\text{AFR})^{0.8} \quad \dots \quad (3)$$

or in the dimensionless form as:

$$\frac{\text{SMD}}{D} = A \left[\left(\frac{\sigma_L}{\rho_a V_a^2 D} \right)^{0.45} \cdot (1 + 1/\text{AFR})^{0.5} + B \left(\frac{\eta_L^2}{\rho_L \sigma_L D} \right)^{0.375} \cdot (1 + 1/\text{AFR})^{0.8} \right] \quad (4)$$

where A and B are dimensionless constants, the values of which can be obtained from the experimental data.

The dimensionless group $\sigma_L / \rho_a V_a^2 D$, which is the inverse of Weber number as applied to air properties, represents the ratio of liquid surface tension to air inertia forces while the group $\eta_L^2 / \rho_L \sigma_L D$ simply defines the fuel properties.

The level of correlation between the experimental data collected in this study with the predictions of equation (3) above with $A = 17 \times 10^{-2}$ and $B = 0.1$ is illustrated in Fig. 12 wherein most of the ex-

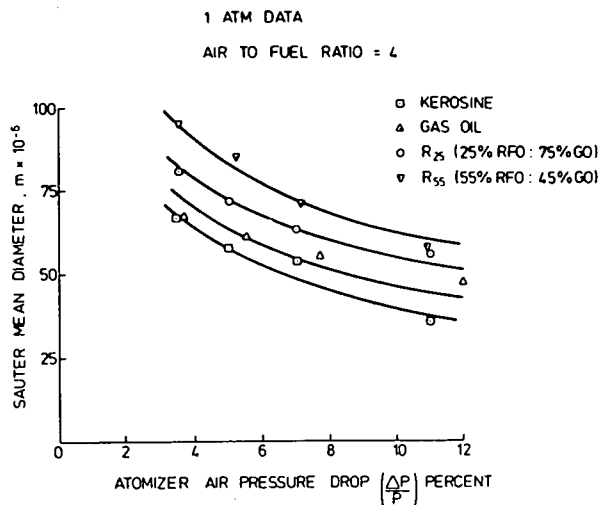


Fig. 7 Effect of varying atomizer air pressure drop and fuel type on mean dropsize

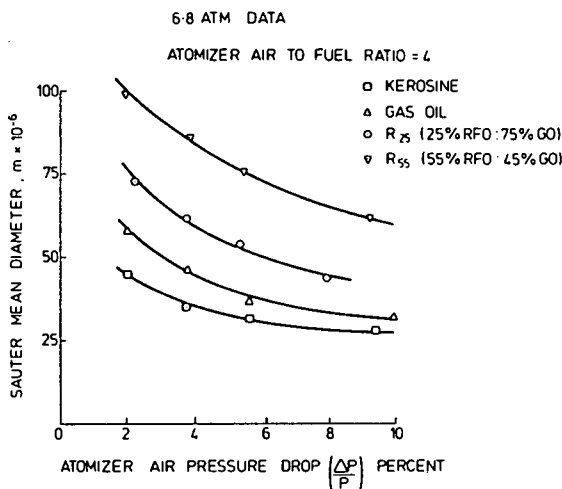


Fig. 8 Effect of varying atomizer air pressure drop and fuel type on mean dropsize

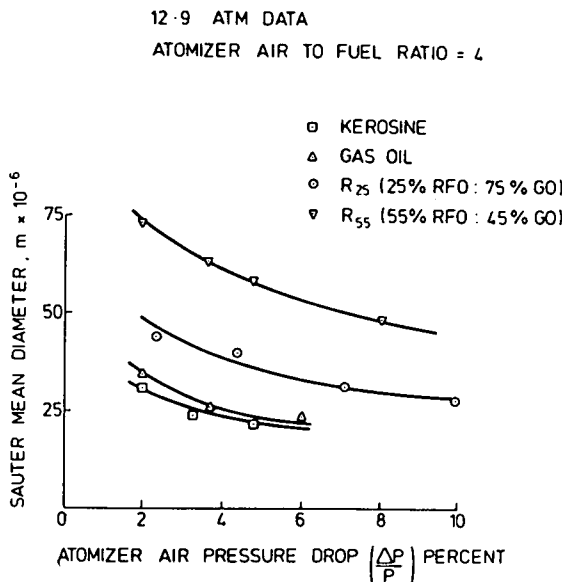


Fig. 9 Effect of varying atomizer air pressure drop and fuel type on mean dropsize

perimental values can be observed to fall within about ± 25 percent of the predicted ones. The largest scatter arising due to the inability of the correlation to predict properly SMD values under atmospheric pressure conditions. It should, however, be noted that this correlation has only been tested for the one specific prefilmer diameter, i.e., $D = 17.5 \times 10^{-3} \text{ m}$.

Discussion

The main differences between this work and that reported previously (see references [1] and [2]) are

- 1 the extended range of atomizing air pressures—from about 1 to 13 atmospheres,
- 2 the extended range of liquid fuel viscosity—up to about 0.037 N s/m^2 , and
- 3 the nature of SMD correlation.

Early work indicated that the air density exponents in the correlating equation were -1.0 and -0.425 for the first and second terms respectively. This work indicates that the air density exponent is -0.45 for the first term and the viscosity-dominated second term is

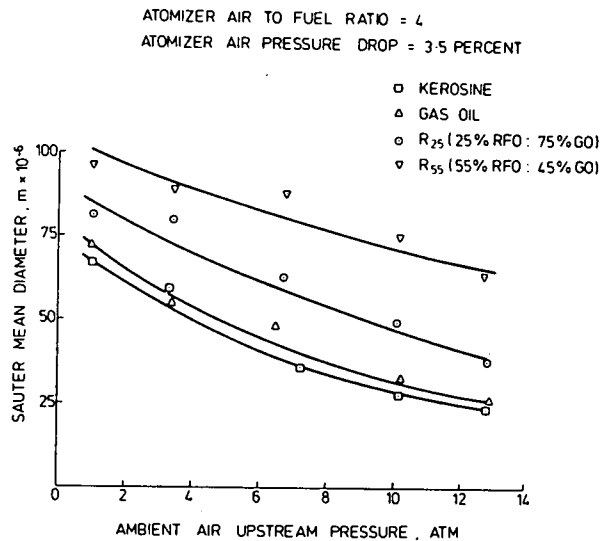


Fig. 10 Atomizer mean dropsize performance under varying ambient air pressures

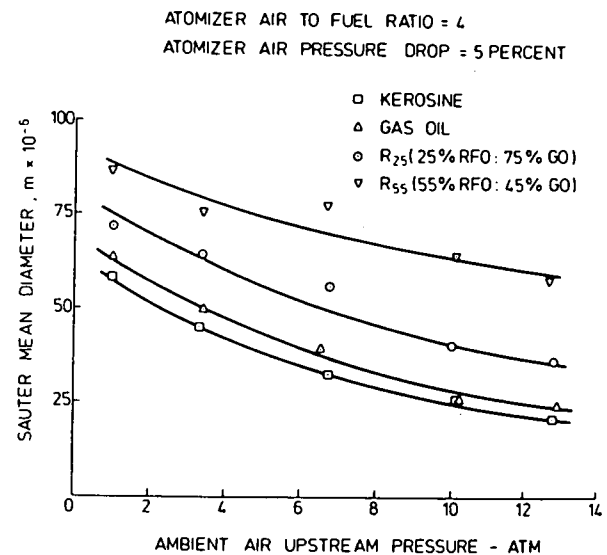


Fig. 11 Atomizer mean dropsize performance under varying ambient air pressures

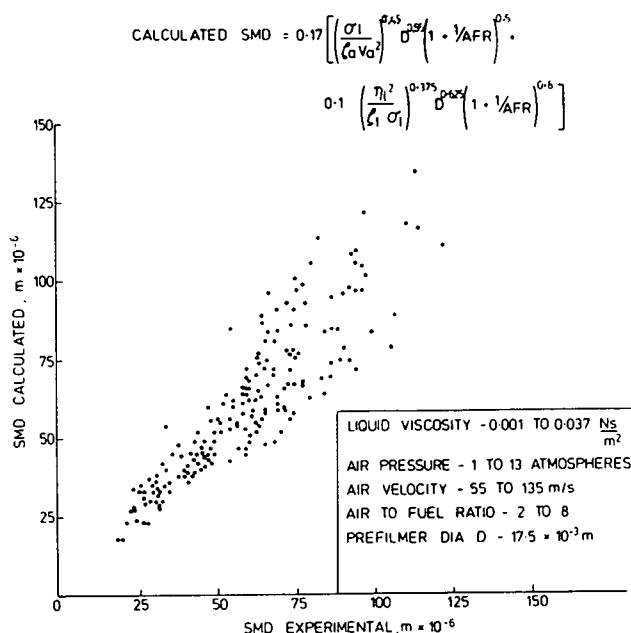


Fig. 12 Comparison of calculated and experimental SMD values

independent of the air density influence. These differences can be explained by the facts that

- 1 the data presented in this paper were obtained under closely controlled conditions, i.e., all variables with the exception of air density were held constant—this was not so in the early work. This accounts for the observed difference with respect to the influence of air density upon the first term of the SMD correlating equation.
- 2 the effect of air density upon the viscosity-dominated second term in the correlating equation had not been examined experimentally in the earlier studies.

It should be pointed out that, as in the previous study, the contribution of the viscosity-related second term in equation (3) changes from one of insignificance for the low-viscosity kerosine fuel to that of increasing significance for the higher-viscosity fuels. This is particularly so when operating at higher pressures.

Conclusions

- 1 The spray Sauter Mean Diameter performance of the atomizer studied in the present investigation, featuring a prefilmer diameter of $17.5 \times 10^{-3} \text{ m}$, is predicted with a reasonable degree of accuracy by the following dimensionally consistent equation:

$$\text{SMD} = 17 \times 10^{-2} \left[\left(\frac{\sigma_l}{\rho_a V_a^2} \right)^{0.45} \cdot (D)^{0.55} \cdot (1 + 1/\text{AFR})^{0.5} + 0.1 \left(\frac{\eta_l^2}{\rho_l \sigma_l} \right)^{0.375} \cdot (D)^{0.625} \cdot (1 + 1/\text{AFR})^{0.8} \right]$$

over the following ranges of operating conditions:

liquid viscosity	= 0.001 to 0.037 Ns/m ²
liquid surface tension	= 0.027 to 0.074 N/m
atomizer air to fuel ratio	= 2 to 8
air velocity	= 55 to 135 m/s
air pressure	= 1 to 13 atmospheres

It must be noted, however, that the experimental verification of the influence of prefilmer diameter D upon the SMD equation must await results from atomizers of different dimensions.

2 The contribution of the viscosity-dominated second term in the above equation changes from one of insignificance for the low-viscosity kerosine fuel to that of increasing significance for the higher-viscosity fuels. This is particularly so when operating at higher pressures with high-viscosity fuels.

3 In the case of low-viscosity kerosine fuel, the influence upon SMD performance of atomizer air to fuel ratio variation (within the 2 to 8 range) is confined to the near atmospheric pressure condition only—there being no significant effect under higher pressure conditions. For the higher-viscosity fuels this influence extends higher up the pressure range.

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Plain-Jet Airblast Atomization of Alternative Liquid Petroleum Fuels Under High Ambient Air Pressure Conditions

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An investigation has been conducted of the effects that air and fuel properties have upon the spray mean dropsize characteristics of a plain-jet airblast atomizer of the type employed in the gas turbine engine. The fuels tested included kerosine, gas oil and a high-viscosity blend of gas oil in residual fuel oil. The tests covered a wide range of ambient air pressures. Well established laser light-scattering technique was employed for dropsize measurements. The experimental data collected in the present investigation are presented in this paper and comparisons are made against similar data relating to the pre-filming type of airblast atomizer, collected in an earlier study (2).

NOMENCLATURE

SMD	=	Sauter Mean Diameter, m
V	=	Velocity, m/s (1m/s = 3.28 ft/s)
D	=	diameter of fuel orifice, m
$\frac{\Delta P}{P}$	=	atomizer air pressure drop, percent
P	=	Pressure, atmosphere (1 atm = 14.696 lbf/in ²)
AFR	=	air to fuel (liquid) mass ratio
ρ	=	density, kg/m ³ (1 kg/m ³ = 0.0624 lb/ft ³)
σ	=	surface tension, N/m (1 N/m = 1000 dynes/cm)
η	=	dynamic viscosity, Ns/m ² (1 Ns/m ² = 0.02089 $\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}$)

Subscripts

a	=	air
l	=	liquid
f	=	fuel

INTRODUCTION

Gas turbines may in the near future be forced to burn low-grade fuels in order to overcome the possible shortages of the more highly-refined petroleum derived fuels. As the demand for the highly-refined middle-distillate type of fuels outstrips the supply, intensive and consequently expensive hydrocracking of the heavier and higher boiling range petroleum fractions becomes necessary, and the incentives for broadening of the fuel specifications will increase. In addition, satisfactory utilization of fuels derived from such alternative sources as oil shales, tar sands, and coal will also have to be catered for in the long range. Consequently the gas turbine may be

required to operate on fuels with increased levels of aromaticity, carbon-to-hydrogen ratio, viscosity, final boiling point etc. The need to minimize the adverse impact upon combustion performance of poor spray quality and evaporation rates resulting from the degradation in fuel properties, therefore, becomes clearly evident.

For some time now there has been pressure to limit the emission of gas turbine generated exhaust pollutants, and it seems unlikely that this pressure will be significantly relaxed as the fuel quality deteriorates. Of the various advanced combustor concepts being actively researched in order to control pollutant formation, the variable-geometry, lean, pre-mixed, pre-vaporized concept appears to offer most hope of success. In its ideal form, this concept would feature the modulation of combustor primary zone airflow in proper proportions throughout the entire engine operating range, complete fuel evaporation and thorough mixing of fuel with air prior to combustion, efficient burning of homogenous mixture of controlled concentration with minimum of pollutant formation. Avoidance of droplet burning combined with a uniformly mixed, lean, primary zone can significantly reduce oxides of nitrogen emissions due to the low reaction temperature and the elimination of 'hot spots'. However, the design of such advanced combustors requires good spray atomization and vaporization performance which can only be confirmed by experimental data concerning actual drop sizes and their vaporization characteristics over a wide range of gas turbine operating conditions. Consequently the stimulus for focusing attention upon the details of such combustion processes as spray atomization and evaporation stems from the requirement to burn satisfactorily the highly-viscous less-volatile lower-grade fuels with a minimum of pollutant formation. It is clear from the foregoing that there is a growing need for experimental data aimed at quantifying these effects in gas turbine combustors.

The work reported here is a continuation of that published earlier. Reference 1 details the atomization performance characteristics of a variety of gas turbine fuel atomizers when spraying under atmospheric pressure conditions covering a wide range of test fuels. Reference 2 extends this data on the pre-filming airblast atomizer to cover the high ambient air pressure conditions. The purpose of this paper is to present similar high ambient air pressure data for another type of airblast atomizer - the plain-jet design. This simpler form of airblast atomizer has hitherto not been subjected to the detailed examination as has its pre-filming counterpart. The earlier plain-jet investigations (see references 3 and 4) contain no high ambient air pressure atomization data whatsoever. Clearly, therefore, more information is required on the performance of a plain-jet airblast atomizer, representative of current gas turbine practice, over a wide range of operating ambient air pressures/fuel viscosities that are of relevance to the gas turbine engine.

THE EXPERIMENTAL PROGRAMME

The fuels selected for this study comprised kerosine, gas oil, and a high-viscosity blend of gas oil in residual fuel oil, type BS 2869 Class C, 3500 seconds Redwood One (860 cSt). The blend was designated R55, as it contained 55 percent residual fuel oil (by volume) and 45 percent gas oil. This allowed the viscosity of the test fuels to be varied over a wide range (see Table 1.).

A plain-jet airblast atomizer was selected for this phase of investigation. Superior atomization performance of the airblast atomizer over the pressure jet type has led to its wide spread use in the modern high pressure ratio industrial as well as aircraft type of gas turbines. The airblast atomizer spray is finer in character, and this, combined with the thorough mixing of fuel and air achieved as an integral part of the atomization process, yields a flame with low levels of luminosity and soot, resulting in relatively cooler liner walls and a minimum of exhaust smoke. Another useful asset of the airblast system is that the fuel placement in the combustion zone is almost independent of the operating fuel flow-being dictated mainly by the air flow pattern. As a consequence, airblast atomizers offer an important practical advantage

from the viewpoint of nozzle guide vane/turbine blade life development in that the outlet temperature profile of the combustor efflux gases is sensibly constant under all operating conditions and consequently may be predicted satisfactorily from experiments conducted at convenient operating conditions, as for example lower levels of combustor pressure. Most of the gas turbines feature airblast atomizers of the pre-filming type, wherein the fuel is first spread into a thin sheet that is sandwiched between two high velocity airstreams in order to promote high rates of shear (see reference 2). This requires the provision of two separate air flow passages within the atomizer body and consequently the design tends to be somewhat complicated and expensive. The plain-jet airblast atomizer, of the type shown in figure 1, is therefore sometimes preferred. This atomizer features merely a conventional air swirler, just downstream of which fuel issues out of plain circular holes in the form of discrete jets. These jets, numbering one per air annulus of the swirler in the atomizer under investigation here, undergo in-flight disintegration without any prior preparation such as fuel pre-filming.

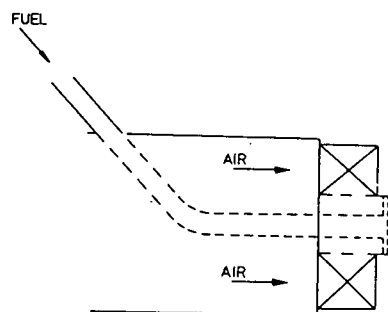


FIG.1. THE PLAIN JET AIRBLAST ATOMIZER - OUTLINE ARRANGEMENT

EXPERIMENTAL DETAILS

The atomizer operating conditions covered the following range of air properties:-

Atomizing air pressure:- from about 1 to 14 atmospheres

Atomizing air pressure drop:- from about 2 to 12 percent, being wider than that normally encountered in gas turbine combustors

Atomizer air to fuel mass ratio:- from about 2 to 12

Atomizing air temperature:- from about 15°C for the 1 atmosphere runs to a maximum of 40°C for the 14 atmosphere runs.

An outline arrangement of the test facility is shown in figure 2. The atomizer was mounted in a pressure chamber connected to a high pressure air supply system comprising multistage Howden compressors. Optical windows were fitted to the chamber to enable

TABLE 1.

PHYSICAL PROPERTIES OF TEST FUELS

Fuel Property	Kerosine	Gas Oil	55% RFO 45% GO
Density ρ_l in Kg/m ³ at 15°C	784	846	913
Surface tension σ_l in N/m at 20°C	0.0277	0.0299	0.0331
Dynamic viscosity η_l in Ns/m ² at 15°C	0.0013	0.0053	0.0749
at 25°C	-	0.0040	0.0435
at 35°C	-	0.0031	0.0275

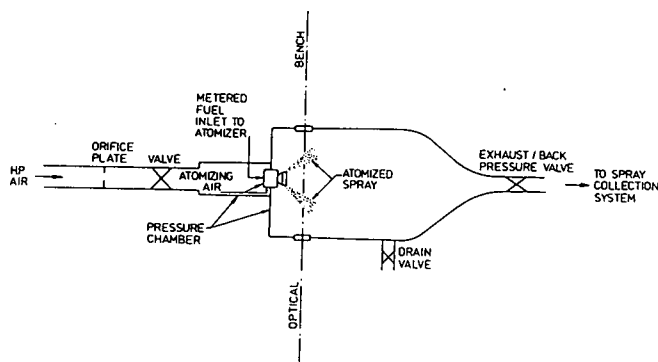


FIG. 2. OUTLINE ARRANGEMENT OF THE TEST INSTALLATION

laser beam access for measuring the atomized spray Sauter Mean Diameter. The air mass flow rate was measured in accordance with BS 1042 and the fuel mass flow rate was measured using precision flowmeters, previously calibrated for each fuel at the appropriate working temperature.

The spray Sauter Mean Diameters were measured using the well-established laser light-scattering technique, an extension of that developed by Dobbins et al (reference 5). This technique was also employed in the earlier work (references 1 and 2) and is based upon the principle of forward diffractive scattering of a parallel, monochromatic beam of light as it passes through the test spray. For more details of the optical bench see references 1 and 5. It is generally believed that spray SMD's down to about 20 microns can be measured reasonably accurately.

RESULTS AND DISCUSSION

Fuel Characterization

The physical properties of the various test fuels are detailed in table 1. The mean dynamic viscosities, in Ns/m^2 , of the different test fuels together with their working temperatures for the ensuing atomization results were: Kerosine- 0.0013 (15°C approx.); gas oil - 0.0053 (15°C approx.); R_{55} - 0.035 (30°C approx.)

Influence of Design and Operating Variables

The experimental results collected in this investigation permit an evaluation of the influence that the following factors have upon the mean droplet size:

- atomizer/swirler air-to-fuel ratio (AFR)
- air pressure drop across the atomizer
- atomizing air ambient pressure
- fuel viscosity

Figures 3 and 4 detail the effect that the atomizer AFR has upon SMD performance for low-viscosity kerosine and high-viscosity R_{55} fuel, respectively. In both cases AFR variation seems to have a slight influence upon the atomization quality only at lower ambient air pressures. The results indicate that the optimum AFR is around 3, and designing for high values will only result in oversized atomizers.

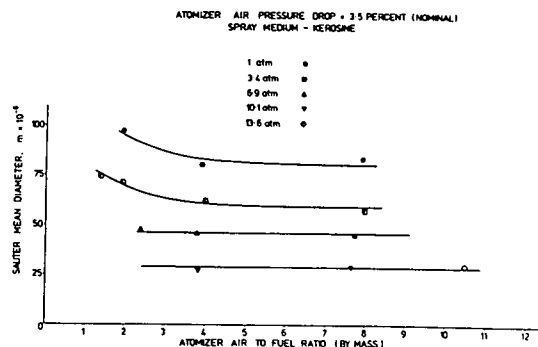


FIG. 3. ATOMIZER MEAN DROPSIZE PERFORMANCE UNDER VARYING AIR TO FUEL RATIO AND AMBIENT AIR UPSTREAM PRESSURE (KEROSINE)

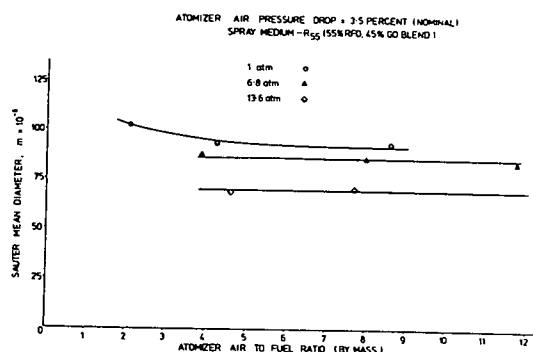


FIG. 4. ATOMIZER MEAN DROPSIZE PERFORMANCE UNDER VARYING AIR TO FUEL RATIO AND AMBIENT AIR UPSTREAM PRESSURE (R_{55} FUEL)

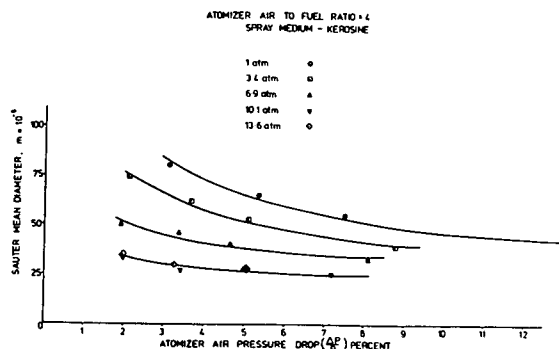


FIG. 5. INFLUENCE OF VARYING ATOMIZER AIR PRESSURE DROP AND AMBIENT AIR UPSTREAM PRESSURE ON SPRAY MEAN DROPSIZE (KEROSINE)

The influence of atomizer air pressure drop upon mean dropsizes performance for various levels of ambient air pressure is illustrated in figure 5 for kerosine, and in figure 6 for the high-viscosity R_{55} fuel. The beneficial influence of increased levels of atomizer air pressure drop (i.e. atomizing airstream velocity) upon SMD performance is clearly evident from both these figures. This influence, however, is seen to diminish noticeably with an increase in ambient air pressure.

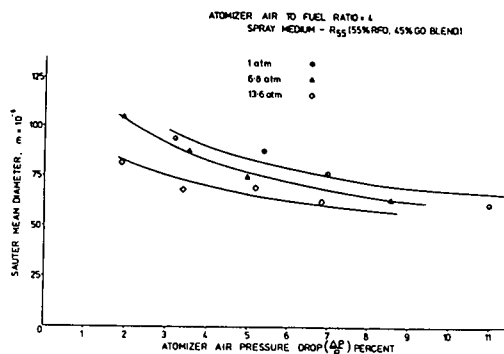


FIG. 6 INFLUENCE OF VARYING ATOMIZER AIR PRESSURE DROP AND AMBIENT AIR UPSTREAM PRESSURE ON SPRAY MEAN DROPSIZE (R₅₅ FUEL)

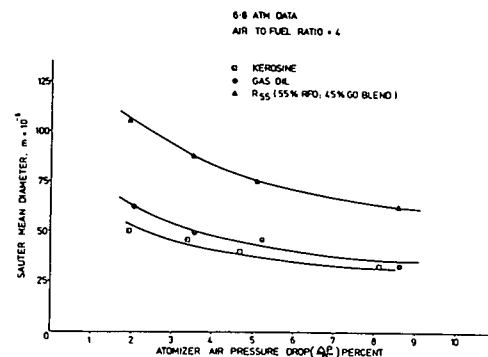


FIG. 8 EFFECT OF VARYING ATOMIZER AIR PRESSURE DROP AND FUEL TYPE ON MEAN DROPSIZE - 6.8 ATM DATA

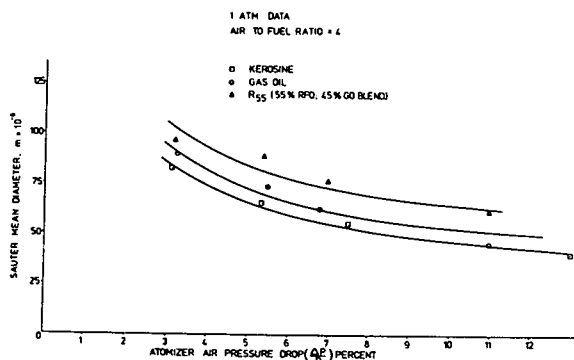


FIG. 7 EFFECT OF VARYING ATOMIZER AIR PRESSURE DROP AND FUEL TYPE ON MEAN DROPSIZE - 1 ATM DATA

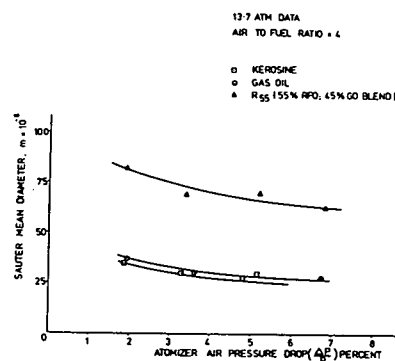


FIG. 9 EFFECT OF VARYING ATOMIZER AIR PRESSURE DROP AND FUEL TYPE ON MEAN DROPSIZE - 13.7 ATM DATA

The mean dropsize versus atomizer air pressure drop data relating to the different test fuels can be cross-plotted in order to illustrate more clearly the influence that fuel quality degradation has upon atomization performance. The results obtained are shown in figures 7 - 9 for 1, 6.8 and 13.7 atmospheres respectively. It should be noted that the ambient air pressures quoted are the actual nominal atomizer upstream air pressures except in the 1 atmosphere case, wherein the pressure of 1 atmosphere was, due to practical considerations, that prevailing downstream of the atomizer.

The influence of atomizing air ambient pressure, or alternatively the atomizing airstream density for the entire range of fuels covered in this study, is illustrated in figures 10 and 11 for two typical atomizer air pressure drop levels. It is clearly evident from these figures that the mean dropsize performance improves more significantly for the low-viscosity kerosine/gas oil type of spray media than for the higher-viscosity R₅₅ fuel with increasing air density. An important practical implication of this finding is that the trend towards such high-viscosity fuels presents a formidable challenge as regards the attainment of good atomization performance.

Comparison with Pre-filming Airblast Atomizers

Figures 12 and 13 are included to provide performance comparisons between the plain-jet and the pre-filming airblast atomizers under varying ambient air pressures. (The experimental data for the pre-filming airblast atomizer were obtained from reference (2), under nominally comparable operating conditions). These figures reveal only slight differences in the experimentally measured mean dropsize characteristics, especially at higher ambient air pressures with low-viscosity kerosine type of spray medium. These results are encouraging and would indicate that the simpler, plain-jet airblast atomizer is worthy of further study.

ANALYSIS OF RESULTS

Systematic evaluation of the low-viscosity kerosine experimental data revealed them to correlate satisfactorily with an equation of the following form:-

$$SMD \propto \left(\frac{\sigma_l}{\rho_a v_a^2} \right)^{0.45} \cdot (1 + 1/AFR)^{0.5} \quad \dots (1)$$

where the atomizing airstream velocity v_a can be computed from the atomizer air pressure drop measurements using the compressible flow theory.

ATOMIZER AIR TO FUEL RATIO = 4
ATOMIZER AIR PRESSURE DROP = 3.5 PERCENT

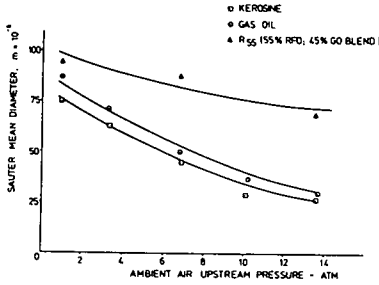


FIG. 10. ATOMIZER MEAN DROPSIZE PERFORMANCE UNDER VARYING AMBIENT AIR PRESSURES

ATOMIZER AIR TO FUEL RATIO = 4
ATOMIZER AIR PRESSURE DROP = 5 PERCENT

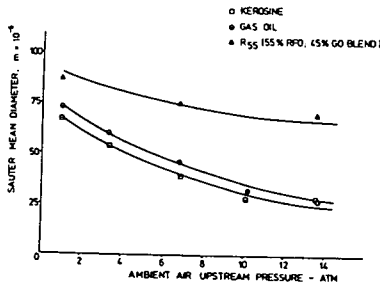


FIG. 11. ATOMIZER MEAN DROPSIZE PERFORMANCE UNDER VARYING AMBIENT AIR PRESSURES

As in the case of the earlier study (2), the high-viscosity dropsizes data analysis indicated that the fuel viscosity influence was apparently somewhat independent of air velocity and density. Accordingly, the high-viscosity data were examined and found to correlate with an equation of the form:-

$$\begin{aligned} \text{SMD} = A_1 \left(\frac{\sigma_l}{\rho_a v_a^2} \right)^{0.45} \cdot (1 + 1/\text{AFR})^{0.5} + \\ B_1 \left(\frac{\eta_l^2}{\sigma_l \rho_l} \right)^{0.4} \cdot (1 + 1/\text{AFR})^{0.8} \quad \dots(2) \end{aligned}$$

It can be readily seen that equation 2 above is not dimensionally consistent and consequently A_1 and B_1 are not dimensionless constants. However, it can be made dimensionally consistent by introducing the diameter of the fuel orifice D as given below:-

$$\begin{aligned} \text{SMD} = A \left(\frac{\sigma_l}{\rho_a v_a^2} \right)^{0.45} \cdot (D)^{0.55} \cdot (1 + 1/\text{AFR})^{0.5} + \\ B \left(\frac{\eta_l^2}{\sigma_l \rho_l} \right)^{0.4} \cdot (D)^{0.6} \cdot (1 + 1/\text{AFR})^{0.8} \quad \dots(3) \end{aligned}$$

ATOMIZER AIR TO FUEL RATIO = 4
ATOMIZER AIR PRESSURE DROP = 3.5 PERCENT
SPRAY MEDIUM - KEROSENE

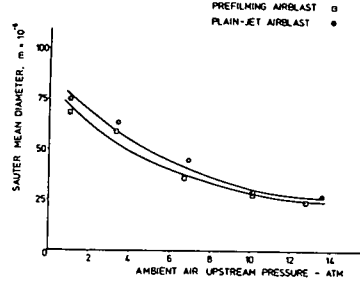


FIG. 12. COMPARATIVE PERFORMANCE OF PREFILMING AND PLAIN-JET AIRBLAST ATOMIZERS UNDER VARYING AMBIENT AIR UPSTREAM PRESSURES - KEROSENE

or in the dimensionless form as:-

$$\begin{aligned} \frac{\text{SMD}}{D} = A \left(\frac{\sigma_l}{\rho_a v_a^2 D} \right)^{0.45} \cdot (1 + 1/\text{AFR})^{0.5} + \\ B \left(\frac{\eta_l^2}{\sigma_l \rho_l D} \right)^{0.4} \cdot (1 + 1/\text{AFR})^{0.8} \quad \dots(4) \end{aligned}$$

where A and B are dimensionless constants.

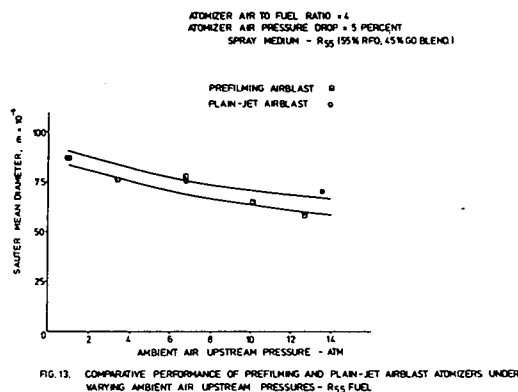
The dimensionless group $\frac{\sigma_l}{\rho_a v_a^2 D}$ is the

inverse of the Weber number as applied to air properties and represents the ratio of liquid surface tension to aerodynamic forces while the group $\frac{\eta_l^2}{\sigma_l \rho_l D}$ simply defines the fuel

properties.

The correlation outlined in equation (2) above is preferred because the influence of fuel orifice diameter D and swirler geometry has not been experimentally examined in this investigation. It is recognised, as a consequence, that further work will be required to cover these variables in order to extend the accuracy and applicability of the correlation evolved herein. The level of agreement between the experimental data collected in this study with the predictions of correlation outlined in equation (2) above with $A_1 = 0.022$ and $B_1 = 14.3 \times 10^{-4}$ (both these values obtained from the experimental data) is illustrated in figure 14. Almost the whole of the experimental data can be observed to fall within ± 30 percent of the predicted values.

It should be noted here that the contribution of the viscosity-dominant second term in the above SMD correlation increases with an increase in fuel viscosity. This contribution changes from that of insignificance for the low-viscosity kerosene fuel to that of increasing significance for the higher-viscosity R_{55} fuel especially under conditions of high ambient air pressures. One important practical



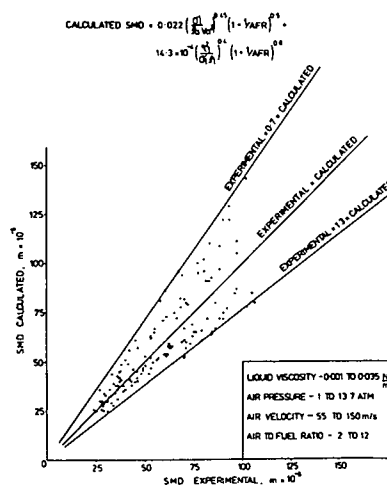
implication of this is that regardless of how high the atomizing air velocity and density are (i.e. no matter how small the first term in the SMD correlation) there is always a finite mean dropsizes, the value of which will increase with an increase in viscosity of the spray medium. Consequently the trend towards high-viscosity low-grade fuels, as stated before, presents a formidable challenge as regards the attainment of good atomization performance.

The SMD correlation developed above for the plain-jet airblast atomizer is found to be generally similar to that for the pre-filming type (see reference 2) and this reinforces the earlier observation that the effect of air and fuel properties upon the mean dropsizes is broadly similar for these two types of airblast atomizers. As a result further work in the form of photographic studies examining the liquid sheet and jet break up in order to identify the detailed mechanism of drop formation under conditions of high ambient air pressure may, not only prove worthwhile from atomizer design viewpoint, but also help explain the observed similarity in dropsizes behaviour of these atomizers.

CONCLUSIONS

The main conclusions that can be drawn from this investigation are as follows:

- 1) Despite the simple design of the plain-jet airblast atomizer, its experimentally measured mean dropsizes characteristics are only slightly different from those of the pre-filming type, especially when operating on low-viscosity kerosene type of fuel under higher ambient air pressures. This simple form of airblast atomizer is, therefore, worthy of further study.
- 2) The beneficial effect of increased levels of ambient air pressure upon mean dropsizes is shown to be much reduced in the case of high-viscosity fuels, thus making the attainment of good atomization performance on such fuels difficult.
- 3) The mean dropsizes data collected in this plain-jet airblast atomization study can be correlated, reasonably accurately, by the



following equation:

$$SMD = 0.022 \left(\frac{\sigma_l}{\rho_a v_a^2} \right)^{0.45} \cdot (1 + 1/AFR)^{0.5} + 14.3 \times 10^{-4} \left(\frac{\eta_l^2}{\sigma_l \rho_l} \right)^{0.4} \cdot (1 + 1/AFR)^{0.8}$$

Over the following ranges of operating conditions:

liquid viscosity	= 0.001 to 0.035 Ns/m ²
liquid surface tension	= 0.027 to 0.074 N/m
atomizer air to fuel mass ratio	= 2 to 12
air velocity	= 55 to 150 m/s
air pressure	= 1 to 14 atmospheres

ACKNOWLEDGEMENTS

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Penetration and Break-Up Studies of Discrete Liquid Jets in Cross Flowing Airstreams

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Penetration and breakup characteristics of a discrete liquid jet injected into a high-velocity cross flowing airstream were investigated as a basis of plain-jet airblast atomizer design. The main variables covered in this phase were, airstream velocity (from about 35 to 150 m/s), liquid jet velocity (from about 5 to 25 m/s) and injection orifice diameter (from about 0.5 to 2.5 mm). The tests were conducted under conditions of normal atmospheric pressure and temperature using still photography for penetration profile and a laser light scattering technique for mean droplet size determination. The experimental penetration data is shown to agree, reasonably accurately, with a relatively simple model developed in the paper. The analysis of the experimental breakup data reveals the airstream velocity as exercising the strongest influence upon Sauter Mean Diameter.

NOMENCLATURE

C_D	Liquid jet drag coefficient
C_d	Liquid droplet drag coefficient
d	Diameter, m
g	Acceleration due to gravity (9.81 m/s ²)
Re	Reynolds number
s	Curvilinear distance along the jet, m
SMD	Sauter Mean Diameter, micron
t	Time, second
v	Mean velocity, m/s
We	Weber number
x	Distance along x-axis from injection orifice centre, m
y	Distance along y-axis from the wall, m
β	Angle of jet with respect to v_a
δ	Angle of relative jet velocity ($\vec{v}_j - \vec{v}_a$) with respect to $\vec{v}_j$
ϵ	Relative distortion of the liquid cross section
ρ	Density, kg/m ³
μ	Absolute viscosity, Ns/m ²
σ	Surface tension, N/m

T	$\frac{v_j}{v_{jo}}$, non-dimensional average jet velocity
λ	$\frac{v_{jo}}{v_a}$, Ratio of average injection to free stream velocity

Subscripts

a	Air
d	Liquid droplet
j	Liquid jet
jr	Relative jet velocity
l	Liquid
o	Injection orifice

INTRODUCTION

The detailed atomization characteristics of the airblast fuel injection systems have been the subject of numerous investigations in recent years due to the importance of efficient fuel preparation to the attainment of good combustion-pollution performance from gas turbine combustors. As a result the merits of airblast atomization are well-established, leading to its widespread adoption in the industrial and aircraft gas turbine engines. Most of the airblast systems now in service are of the pre-filming type, wherein the fuel is first spread out into a thin, continuous sheet and then subjected to the atomizing action of high velocity airstream on both sides. Much interest has grown in recent times, however, in the plain-jet airblast atomizer, as it offers relative to the pre-filming type a much simpler and cheaper system (1), (2). In the plain-jet arrangement, the fuel is not pre-filmed but instead discharged in the form of several discrete jets in the

path of a high velocity airstream, thereby enabling these jets to undergo in-flight disintegration.

The plain-jet airblast atomizer has hitherto not been subjected to the detailed examination as has its pre-filming counterpart. Consequently, its geometry requires to be optimized if we are to deploy the available air in the most effective manner to achieve the best possible level of atomization. The penetration and breakup characteristics of discrete liquid jets in cross flowing airstream would go some way in furthering our understanding of the mechanics of plain-jet atomization and thus enable better systems to be designed in future.

The work reported here is a continuation of that carried out earlier in the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. References 1 and 2 detail the atomization performance results under atmospheric and high pressures respectively of the earlier investigations into the behaviour of a plain-jet airblast atomizer whose geometry had not been optimised.

The purpose of this paper is to present the results of penetration and breakup studies of discrete liquid jets in cross-flowing airstreams due to their direct relevance to the optimization of the plain-jet airblast atomizer design. Investigations outlined in references 3 and 4 relate to the breakup of discrete liquid jets under co-axial airstream conditions and consequently are of limited use. The work of Chelko (ref 5), Ingebo (ref.6), and Schetz and Padhye (ref.7) too is of somewhat limited value due either to the high airstream velocities (significantly higher than those encountered in gas turbine combustors) or the examination of the penetration profile in the near-field region only (i.e. distances of one inch or less). Clearly, therefore, more information is required on the penetration and breakup characteristics of discrete liquid jets in cross-flowing airstream covering a wide range of air, fuel and orifice geometry variables that are of relevance to the gas turbine combustors.

SELECTION OF TEST CONDITIONS

An integrated theoretical-experimental approach was adopted in this investigation. A review of the previously published work in the open literature identified the penetration models of Clark (ref 10) and Le Grives (ref.11) as possibly being the nearest in scope to the present study. The proposed penetration model, outlined briefly in one of the subsequent sections of this paper, is an extension thereof. The situation with regard to the breakup modelling was observed to be far from satisfactory due to the complex nature of disintegration mechanism involved in the process of spray atomization. It was apparent that this was an area where empirical approach would be more appropriate. Furthermore, it became clear that the basic behaviour of a discrete liquid jet was likely to be related to such variables as the air/liquid properties as well as the injector geometry/operating conditions. The major variables selected for the first phase of the experimental investigation were: the airstream velocity, liquid jet's initial velocity and the injection orifice diameter. Consequently, the airstream density; the liquid properties of viscosity, surface tension and density; the angular orientation of the injection orifice, etc, were some of the other major variables left for the subsequent phases. This choice was based upon considerations of cost and complexity.

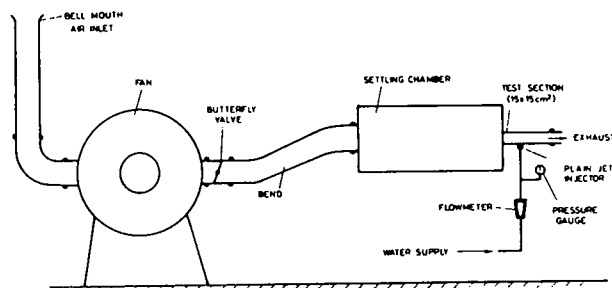


FIG.1 SCHEMATIC DIAGRAM OF TEST RIG.

The actual range of conditions covered in the experiments are detailed below:

Airstream Velocity	from about 35 to 150 m/s
Airstream density	not varied (i.e. corresponding to normal atmospheric pressure and temperature conditions)
Liquid jet velocity	from about 5 to 25 m/s
Injection orifice diameter	0.5 to 2.5 mm
Injection orifice l/d ratio	not varied (i.e. = 5 throughout)
Angular orientation of injection orifice	not varied (i.e. at right angle to the airstream)
Spray medium	not varied (i.e. water)

EXPERIMENTAL DETAILS

A schematic diagram of the test facility is shown in Figure 1. Air at near normal atmospheric pressure and temperature was supplied to a transparent test section (square cross section 12.5 cm x 12.5 cm, and 34 cm long) through a bellmouth located in the settling chamber. The air mass flow was measured in accordance with BS 1042. Provision was made for the measurement of air temperature and velocity profile in the test section through the use of a thermometer and a total head probe.

Water was fed to the plain-jet injector, located in the test section, through a pump and, precision flowmeters were used to measure its mass flowrate. The injectors, featuring circular orifice, were fitted flush to the inside surface of the test section base plate. The injector orifices were designed with a smooth conical entry passage followed by a straight run with an l/d of 5 in order to minimise the contraction losses and thus ensure that the passage ran full. Furthermore, the orifice was located in the centre of the square shaped test section so as to minimise the boundary layer influence upon the liquid jet trajectory and breakup. The orientation of the injection orifice was arranged so as to deliver a jet of liquid normal to the airstream.

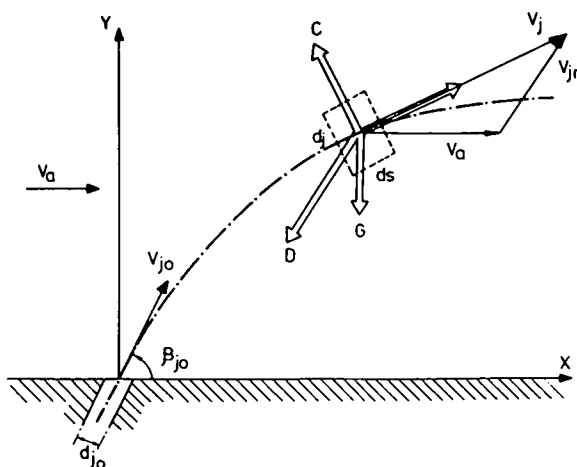


FIG. 2 PARAMETERS USED IN JET PENETRATION ANALYSIS IN THE PRE-DISINTEGRATION RÉGIME

The penetration profiles were determined through the use of wide-view still photography where as the droplet size measurements were made using the well-established laser light-scattering technique. This optical technique, an extension of that developed by Dobbins et al (ref.8) was also employed in the earlier studies (refs.1,2) and is based upon the principles of forward diffractive scattering of a parallel monochromatic beam of light as it passes through the test spray. The technique does not interfere with the spray and gives reasonably accurate assessment of SMDs (down to about 20 microns). Furthermore, it allows results to be obtained quickly and is therefore particularly well suited to this kind of study where a large number of measurements are required over a wide range of atomization conditions. Provision was also made for the movement of the entire optical bench along the axis of the spray in order to determine the extent to which the values of mean dropsize varied with the measuring station distance, with reference to the injector location.

RESULTS

Jet Penetration Model

Upon leaving the injector, the liquid jet remains collimated for a short distance of a few diameters and beyond this instabilities begin to set in as a result of the interaction with the surrounding airstream. Consequently, the jet cross section becomes distorted and the jet rapidly disintegrates to yield ligaments that are unstable in character and as a result undergo further breakup to yield drops (ref.9). The resulting droplet trajectories are a function of the prevailing flow-field. The analysis presented in this section is based upon the division of the flow-field into two régimes, pre and post jet disintegration régimes, each with its own assumptions and mathematical treatment. The parameter distinguishing the first régime from the second is a

modified form of that originally proposed by Clark (ref.10) and is described in this section at a later stage.

Pre-Disintegration Régime. The assumptions underlying the model in the pre-jet disintegration régime are:

- the airstream is free of recirculation and has uniform velocity profile
- the flow is subsonic and consequently free of shockwave interactions
- the air flow is non-viscous and incompressible
- the flow is two-dimensional and steady
- the liquid jet cross-section remains circular along its path
- liquid jet flow properties of density and velocity are uniform across any cross-section
- the liquid jet undergoes no entrainment/mass diffusion
- the liquid jet is free of swirl and possesses velocity along its axis only

The analysis that follows here is a modified version of that originally proposed by Le Grives (ref.11) and incorporates the term relating to the weight of the liquid jet element. Liquid, at velocity V_{jo} , is injected at an angle β_{jo} from a circular orifice (of diameter d_{jo}) into a uniform subsonic airstream with a velocity V_a (see Figure 2). The various forces interacting on a liquid element of diameter d_j and length ds are :

- the centrifugal force C , oriented normal to the jet centre line
- the overall drag force D , opposing the relative velocity of the jet, $\vec{V}_j - \vec{V}_a = \vec{V}_{jr}$
- the rate of variation of momentum M , along the jet trajectory
- the weight G , of the liquid element

The above forces take the following form :

$$C = \rho_j V_j^2 \frac{d\beta}{ds} \frac{\pi}{4} d_j^2 ds$$

$$D = C_D \frac{\rho_a V_{jr}^2}{2} \sin\delta d_j ds$$

$$M = \rho_j V_j \frac{dV_j}{ds} \frac{\pi}{4} d_j^2 ds$$

$$G = \frac{\pi}{4} d_j^2 ds (\rho_j - \rho_a) g$$

Conducting a balance of forces along and normal to the jet trajectory yields the following equations:

$$\frac{d\beta}{ds} = -2 \frac{\rho_a V_a^2}{\rho_j V_j^2} \frac{C_D}{\pi d_j} \sin^2 \beta - \frac{(\rho_j - \rho_a)}{\rho_j} \frac{g}{V_j^2} \cos \beta \quad \text{---(1)}$$

$$\frac{dv_j}{ds} = -2 \frac{\rho_a v_a^2}{\rho_j v_j^2} \frac{C_D}{\pi d_j} v_j \left(\frac{v_j}{v_a} - \cos \beta \right) \sin \beta - \left(\frac{\rho_j - \rho_a}{\rho_j} \right) \frac{g}{v_j} \sin \beta \quad \text{--- (2)}$$

Since the jet is still collimated in the pre-jet disintegration régime, the equation for conservation of mass yields:

$$v_j d_j^2 = v_{jo} d_{jo}^2 \quad \text{--- (3)}$$

Dividing equation (2) by (1) and introducing $\lambda = \frac{v_{jo}}{v_a}$ and $T = \frac{v_j}{v_{jo}} = \left(\frac{d_{jo}}{d_j} \right)^2$ one is led to the following form of differential equation.

$$\frac{dT}{d\beta} = \frac{C_1 T^{-0.5} (\lambda T - \cos \beta) \sin \beta + C_2 T^{-1} \sin \beta}{C_1 T^{-1.5} \sin^2 \beta + C_2 T^{-2} \cos \beta} \quad \text{--- (4)}$$

$$\text{where } C_1 = 2 \frac{\rho_a}{\rho_j} \frac{1}{\lambda^2} \frac{C_D}{\pi} \frac{v_{jo}}{d_{jo}}$$

$$C_2 = \frac{\rho_j - \rho_a}{\rho_j} \frac{g}{v_{jo}}$$

Also equation (1) can be re-written in the following form:

$$\frac{ds}{d\beta} = - \frac{1}{C_3 T^{-1.5} \sin^2 \beta + C_4 T^{-2} \cos \beta} \quad \text{--- (5)}$$

$$\frac{dx}{d\beta} = - \frac{\cos \beta}{C_3 T^{-1.5} \sin^2 \beta + C_4 T^{-2} \cos \beta} \quad \text{--- (6)}$$

$$\frac{dy}{d\beta} = - \frac{\sin \beta}{C_3 T^{-1.5} \sin^2 \beta + C_4 T^{-2} \cos \beta} \quad \text{--- (7)}$$

$$\text{where } C_3 = 2 \frac{\rho_a}{\rho_j} \frac{1}{\lambda^2} \frac{C_D}{\pi} \frac{1}{d_{jo}}$$

$$C_4 = \frac{\rho_j - \rho_a}{\rho_j} \frac{g}{v_{jo}^2} \quad \text{and}$$

x, y the cartesian co-ordinates denoting the jet penetration y at a distance x from the injection point as a function of the jet angle β .

The above differential equations 4, 5, 6 and 7 can be solved knowing the drag coefficient C_D and the boundary conditions v_{jo} , v_a , d_{jo} and β_{jo} . Predictions of the proposed model in the pre-disintegration régime based upon the assumption of an invariant value of $C_D = 1$ are in best agreement with the experimental data. Examination of drag coefficient data (ref.12) indicates this value to be very appropriate for circular cylinders subjected to the sort of Reynold's numbers covered in the present study.

Breakup Parameter. From a study of the liquid jet breakup in a cross flowing gas, Clark (ref.10) established a breakup criterion based upon the degree of liquid jet spreading (in a direction transverse to the gas flow) as a function of the original jet dimensions. He observed, experimentally, that the numerical value of this breakup parameter, ϵ , was 1 or 2 at the point where the jet breakup first commenced.

However, in the present study it was observed that this value of ϵ afforded unsatisfactory agreement with the experimental penetration profiles over the entire range of conditions studied and consequently a modified form of this parameter was necessary in order to obtain a better penetration prediction model. Evaluation of the experimental data enabled the following revised breakup parameter, ϵ' , to be evolved:

$$\epsilon' = \frac{\epsilon}{S^b} = 3.31 \times 10^{-6} d_{jo}^{-1.14} (1000)^b$$

$$\text{where } \epsilon = 2 \frac{\rho_a}{\rho_j d_{jo}^2} \int_0^t \int_0^t v_{jr}^2 dt dt \quad \text{and}$$

$$b = (447.93 d_{jo})^{0.0759}$$

Post-Disintegration Régime. Here a brief treatment of the equations governing the motion of a drop in a uniform flow is outlined. The underlying assumptions are:

- the liquid drop is a rigid sphere and subject only to the weight and drag forces
- the initial velocity and co-ordinates of the drop correspond to the velocity and co-ordinates of the jet along its centreline at the moment of disintegration
- the initial diameter of the drop equals the liquid orifice diameter
- the droplet undergoes no evaporation or agglomeration
- the inter-drop spacing is large and consequently droplet interaction effects are negligible.

The equations of droplet motion in the cartesian co-ordinates can be written as follows:

$$\frac{\pi}{6} d^3 \rho_j \frac{dv_x}{dt} = - \frac{\pi}{8} d^2 C_D \rho_a (v_a - v_x)^2 \quad \text{--- (8)}$$

$$\frac{\pi}{6} d^3 \rho_j \frac{dv_y}{dt} = - \frac{\pi}{8} d^2 C_D \rho_a v_y^2 - \frac{\pi}{6} d^3 \rho_j g \quad \text{--- (9)}$$

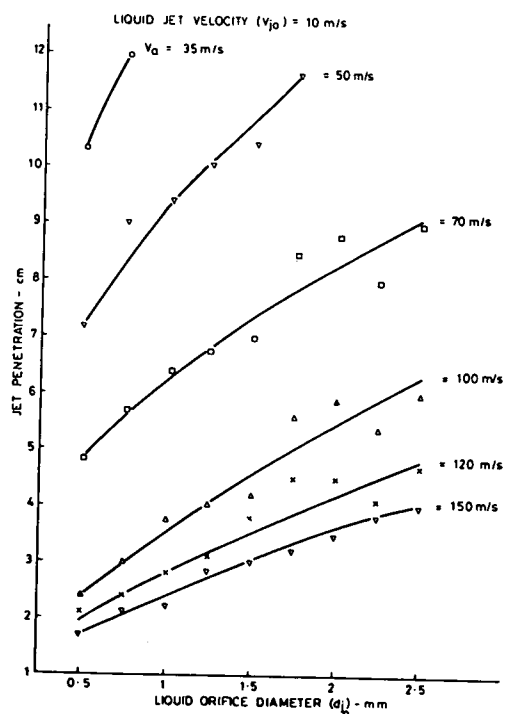


FIG. 3. VARIATION OF PENETRATION WITH LIQUID ORIFICE DIAMETER AT VARIOUS LEVELS OF AIRSTREAM VELOCITY.

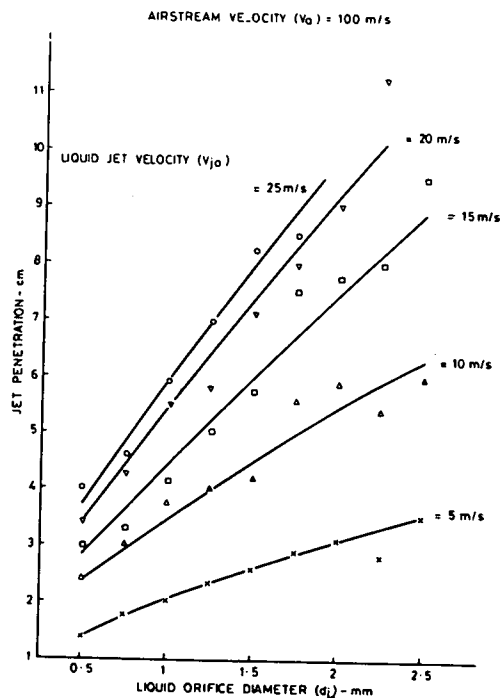


FIG. 4. VARIATION OF PENETRATION WITH LIQUID ORIFICE DIAMETER AT VARIOUS LEVELS OF LIQUID JET VELOCITY.

The droplet drag coefficient C_d in the above equation is not constant due to the changing droplet size and velocity and consequently the droplet Reynold's number. The work of Dickerson and Schuman (ref.14) related the drag coefficient of the liquid droplet to the airstream Reynold's number, Re , in the following manner.

$$C_d = 27 Re^{-0.84} \quad \text{for } 0 < Re \leq 80 \quad \text{---(10)}$$

$$C_d = 0.271 Re^{-0.217} \quad \text{for } 80 < Re \leq 10^4 \quad \text{---(11)}$$

$$C_d = 2 \quad \text{for } Re > 10^4 \quad \text{---(12)}$$

where
$$Re = \frac{\rho_a d_d}{\mu_a} \left[(v_a - v_x)^2 + v_y^2 \right]^{0.5}$$

However, before the above drag data can be utilised information regarding the variation of droplet size along its path is necessary. In the absence of such information, an empirical equation was evolved in order to obtain satisfactory matching of the experimental penetration profiles with the model predictions through the selection of arbitrary droplet sizes. The empirical equation evolved expressed the droplet diameter variation as a function of the gas stream Reynold's and Weber numbers and took the following form:

$$\frac{d d_d}{ds} = - \left(20 \frac{We}{Re} \right)^{3.74} \quad \text{---(13)}$$

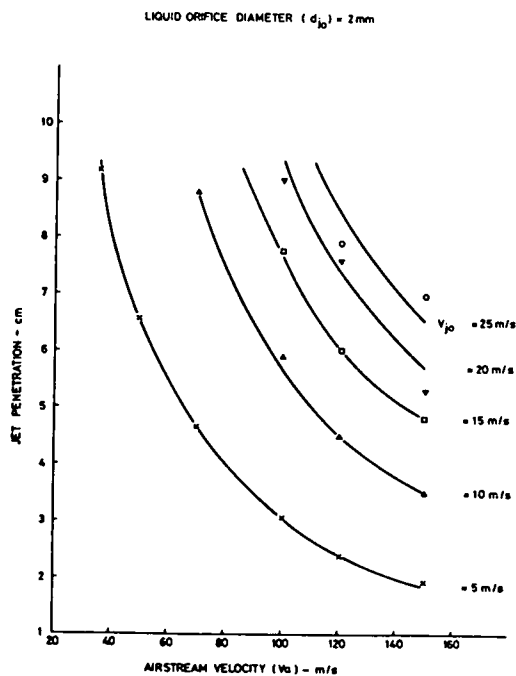


FIG. 5. VARIATION OF PENETRATION WITH AIRSTREAM AND LIQUID JET VELOCITY

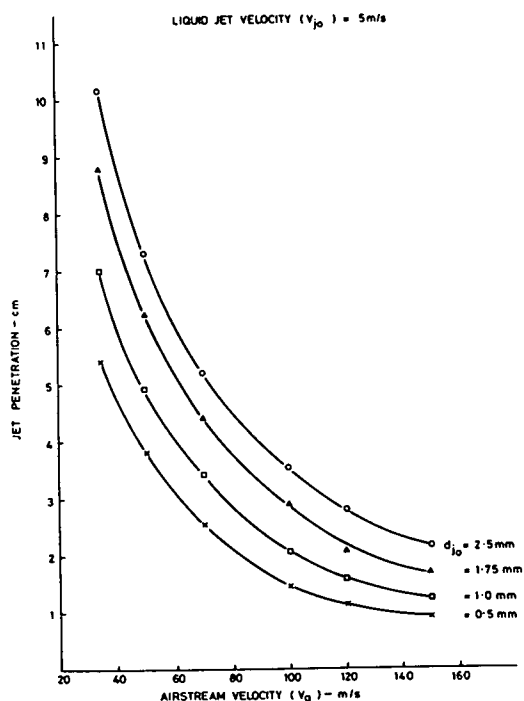


FIG. 6 VARIATION OF PENETRATION WITH AIRSTREAM VELOCITY FOR DIFFERENT INJECTOR ORIFICE DIAMETERS

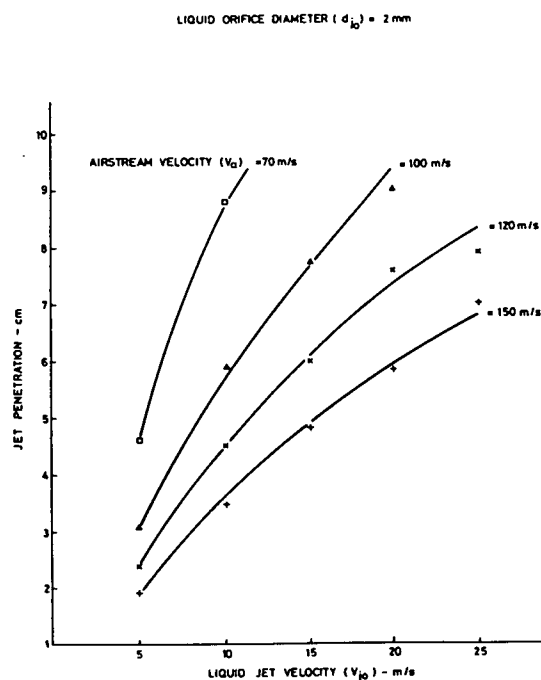


FIG. 7 VARIATION OF PENETRATION WITH LIQUID JET VELOCITY

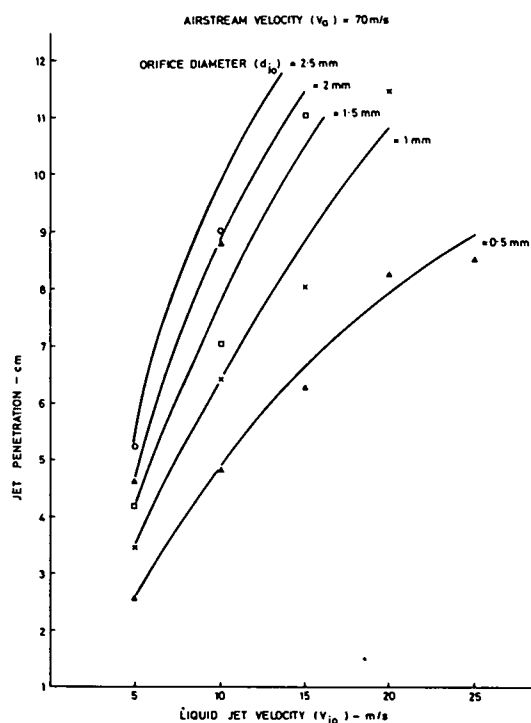


FIG. 8 VARIATION OF PENETRATION WITH LIQUID JET VELOCITY FOR DIFFERENT INJECTOR ORIFICE DIAMETERS

$$\text{where } We = \frac{\rho_a \left[(V_a - V_x)^2 + V_y^2 \right]}{\sigma_l}$$

$$Re = \frac{\left[(V_a - V_x)^2 + V_y^2 \right]^{\frac{1}{2}} \rho_a d_d}{\mu_a}$$

Equations 10, 11, 12 and 13 were introduced into the differential equations of motions 8 and 9, and were solved on VAX/VMI1 computer. The level of agreement realised with the experimental penetration profiles was considered satisfactory and will be discussed in a subsequent section of the paper.

Jet Penetration Experimental

Figures 3 and 4 illustrate the effect of liquid orifice diameter upon the penetration characteristics of the liquid jet for a wide range of airstream and liquid jet velocities respectively. The jet penetration clearly increases with increasing orifice diameter for a fixed level of liquid and airstream velocity. In the present work, penetration was arbitrarily chosen to indicate the distance (along the Y-axis) of the outer visible boundary of the liquid jet at a station some 12 centimetres (along the X-axis) from the injection point.

The influence of airstream velocity upon jet penetration is depicted in Figures 5 and 6. As would be expected, an increase in airstream velocity results in diminished jet penetration as a consequence of increased aerodynamic drag forces acting upon the liquid jet.

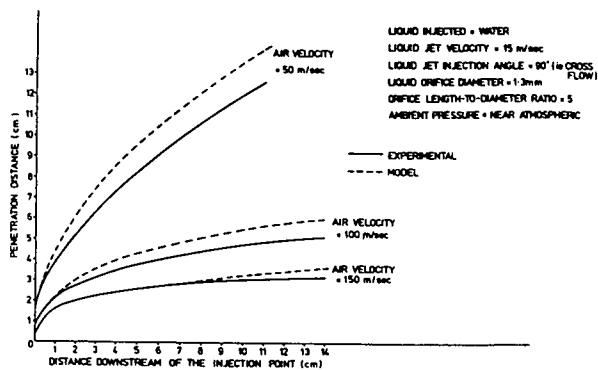


FIG. 9 EFFECT OF AIRSTREAM VELOCITY ON THE PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

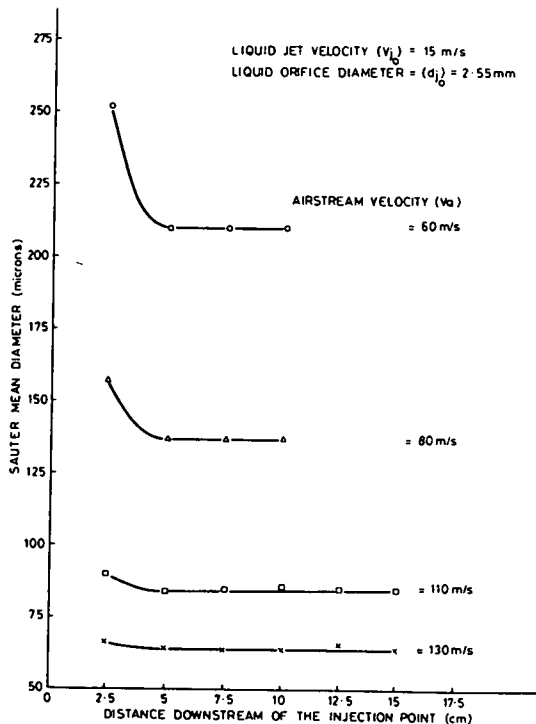


FIG. 10 EFFECT OF MEASURING STATION DISTANCE FOR VARIOUS AIRSTREAM VELOCITIES (V_a) UPON SMD

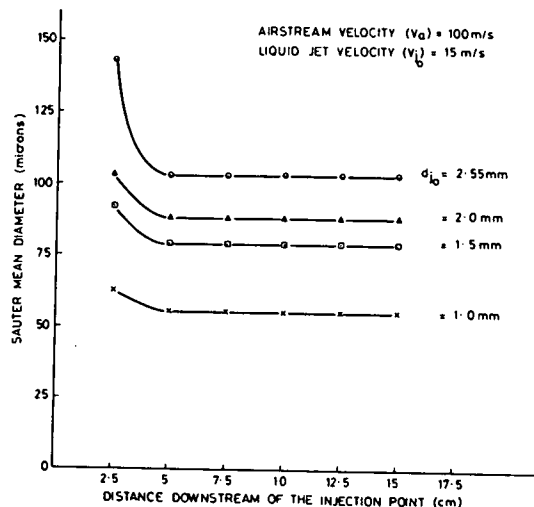


FIG. 11 EFFECT OF MEASURING STATION DISTANCE FOR VARIOUS INJECTION ORIFICE DIAMETERS (d_j) UPON SMD

Comparison of the Experimental Penetration Data with the Model. The experimental penetration profiles discussed above were compared with the predictions of the model outlined in the previous section of this paper and a typical comparison is illustrated in Figure 9 for a range of different airstream velocities. The model predictions were observed to be within about 20 percent of the entire experimental data and were considered satisfactory.

Dropsizes Experimental

Before proceeding with the main investigation concerning the effect of air, liquid and injector geometry variables upon dropsizes, it was considered appropriate to examine the influence of measuring station distance along the spray axis upon mean dropsizes. Figures 10 and 11 illustrate the results obtained and indicate that the variation of spray sampling distance beyond 5 centimetres has no measurable influence upon the mean dropsizes. Consequently all subsequent dropsizes measurements were made at a distance of 5 centimetres from the injection point.

The effect of liquid jet and airstream velocity upon mean dropsizes can be seen in Figure 12. It is clear that the velocity at which the liquid is injected has very little effect upon the resulting mean dropsizes. (Contrast with its noticeable influence upon jet penetration). This lack of SMD dependence upon liquid jet velocity was observed in earlier studies too (refs. 7,14).

The beneficial influence of increased levels of airstream velocity upon spray mean dropsizes for a range of injection orifice diameters is clearly evident from Figure 13. The analysis of this low viscosity data suggests a relationship of the form $SMD \propto V_a^{-1.34}$. This power index of 1.34 is in excellent agreement with that reported by Weiss and Worsham (ref.15) but is somewhat higher than the value of Unity proposed in other studies (refs. 1,3 4).

An increase in liquid jet velocity results in a higher jet penetration for the entire range of airstream velocities and injector orifice diameters covered in this investigation (see Figures 7 and 8). This is again to be expected due to an increase in the momentum of the liquid jet.

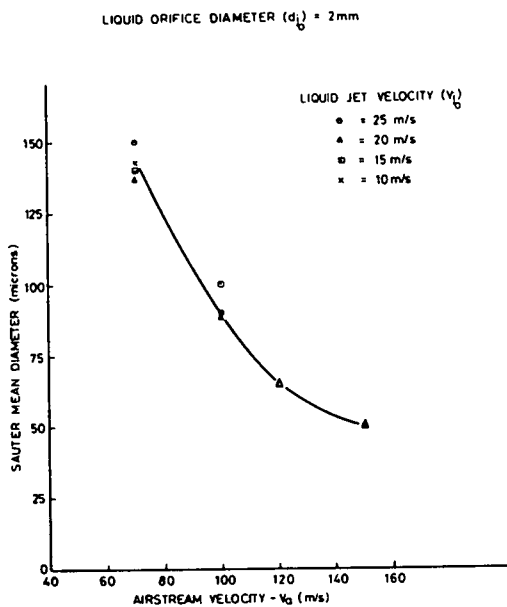


FIG.12. EFFECT OF AIRSTREAM AND LIQUID JET VELOCITY UPON SPRAY MEAN DROPSIZE.

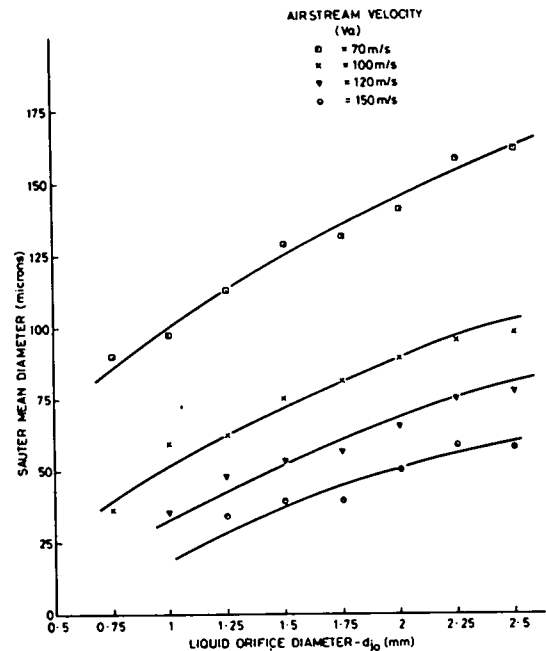


FIG.14. INFLUENCE OF LIQUID ORIFICE DIAMETER UPON SPRAY MEAN DROPSIZE.

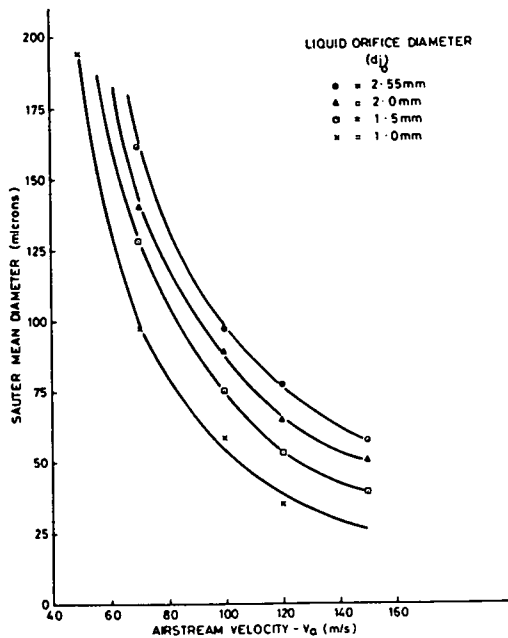


FIG.13. INFLUENCE OF AIRSTREAM VELOCITY UPON SPRAY MEAN DROPSIZE.

Figure 14 illustrates the influence that the diameter of the injection orifice has upon the spray quality. The mean droplet size is observed to increase with an increase in orifice diameter following the relationship $SMD \propto d_{jo}^{0.55}$.

CONCLUSIONS

The main conclusions that can be drawn from this investigation are :

1. The penetration of a liquid jet increases with:
 - an increase in diameter of the injection orifice
 - an increase in injectant velocity and
 - a decrease in airstream velocity
 2. The predictions of the penetration model, developed in the paper, are in reasonable agreement with the experimentally measured penetration profiles.
 3. The variation of the velocity of injected liquid appears to have no significant effect upon the mean droplet size.
 4. The spray mean droplet size is observed to decrease with :
 - an increase in airstream velocity in accordance with the relationship $SMD \propto V_a^{-1.34}$.
- and
- a decrease in the diameter of the injection orifice following the relationship $SMD \propto d_{jo}^{0.55}$.

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PENETRATION AND BREAK-UP BEHAVIOUR OF A DISCRETE
LIQUID JET IN A CROSS FLOWING AIRSTREAM - A FURTHER STUDY

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ABSTRACT

Penetration and break-up characteristics of a discrete liquid jet injected into a high velocity cross flowing airstream were examined as a basis of plain-jet airblast atomizer design. The first results of this program, detailed in (4), covered the effects of liquid jet/airstream velocities and the injection orifice diameter. The results presented here cover the effects of liquid viscosity (0.001 to 0.125 Ns/m²), liquid surface tension (0.027 to 0.074 N/m), liquid density (812 to 1830 Kg/m³), the liquid jet injection angle (30 to 90 degrees) and the orifice length-to-diameter ratio (5 to 14). These tests were carried out under normal atmospheric pressure and temperature conditions using still photography for penetration profile and a laser light scattering technique for mean dropsize determination. The experimental penetration data is shown to agree reasonably accurately, with the simple model developed before (see (4)). The analysis of the experimental mean dropsize data collected in this study leads to the development of the following correlation

$$SMD = 1.206 \left(\frac{\sigma_L}{\rho_L V^2} \right)^{0.6} d_{j0}^{0.4} + 0.072 \left(\frac{\mu_L^2}{\sigma_L \rho_L} \right)^{0.45} d_{j0}^{0.55}$$

NOMENCLATURE

d	Diameter, m
L	Orifice length m
m	Mass flow rate, Kg/s
Re	Reynolds Number
SMD	Sauter Mean Diameter, meter
V	Mean velocity, m/s
We	Weber number
β	Angle of jet with respect of V_a
ρ	Density, Kg/m ³
μ	Absolute viscosity, Ns/m ²

σ Surface tension, N/m

Subscripts

a	Air
j	Liquid jet
L	Liquid
o	Injection orifice

INTRODUCTION

The attainment of satisfactory combustion-pollution performance from gas turbine combustors is generally known to be strongly related to the performance of the fuel injector. Consequently, a variety of fuel injection systems have been the subject of numerous investigations over the years. The quality of atomization, as indicated by the sizes of the drops produced as a result of the fuel disintegration, has been the main feature under examination in order to relate it to the injector design/operating conditions as well as the fuel properties.

The superior combustion-pollution performance of the airblast atomizer has, in recent times, become increasingly apparent, leading to its widespread adoption in the modern gas turbine. In the airblast system intimate mixing of fuel and air is achieved and this results in high rates of shear and consequently a spray that is finer in character. The ensuing combustion is characterised by low levels of smoke, flame radiation and a temperature distribution of the combustor efflux gases that is less susceptible to changes in combustor operating conditions.

Most of the gas turbine engines feature airblast atomizers of the pre-filming type, wherein the fuel is first spread into a thin sheet that is sandwiched between two high velocity airstreams (see (1)). Much interest has grown, in recent times, however, in the plain-jet airblast atomizer, as it offers a system of comparable performance and yet is much simpler and cheaper relative to the pre-filming type (see (2) and (3)). In the plain-jet arrangement the fuel is not pre-filmed, but instead discharged in the form of several

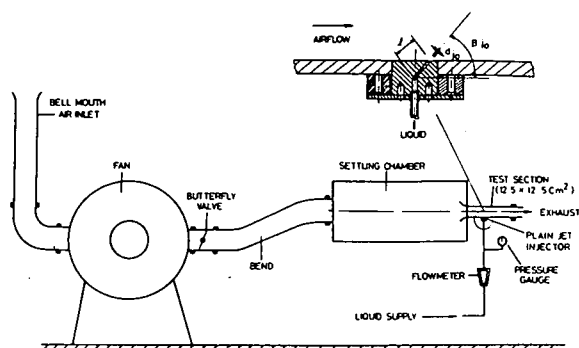


FIG 1 SCHEMATIC DIAGRAM OF TEST RIG

discrete jets into a high velocity airstream thus enabling them to undergo disintegration in-flight. This plain-jet airblast system has hitherto not been subjected to the detailed examination as has its pre-filming counterpart. For instance, the geometry of the plain-jet system requires to be optimized if we are to deploy the available air in the most effective manner to achieve the best possible level of atomization.

In addition to the foregoing, it is anticipated that the quality of the future fuels is likely to deteriorate. Consequently, the gas turbine engines will be required to be more fuel flexible than before and be capable of satisfactory operation on fuels with increased levels of aromaticity, carbon-to-hydrogen ratio, viscosity, final boiling point, etc. The need to minimize the adverse influence upon spray quality/evaporation rates (and hence combustion performance) from such a fuel quality degradation together with the ignorance of the critical design features of the plain-jet airblast atomizer were the prime incentives for undertaking this study.

TABLE 1

PHYSICAL PROPERTIES OF TEST LIQUIDS

1. Gas oil and solution of the synthetic hydrocarbon polymer, Hyvis Polybutene No.05 in Kerosine to obtain a wide range of viscosity.

Liquid Property	Kerosine	Gas Oil	70% Hyvis	85% Hyvis
Density ρ_L in Kg/m^3 @ 20°C	784	846	823	832
Surface tension σ_L in N/m @ 20°C	0.0277	0.0299	0.03008	0.03027
Absolute viscosity μ_L in Ns/m^2 @ 15°C	0.0013	0.0053	0.027	0.072
20 $^\circ\text{C}$			0.0205	0.052
25 $^\circ\text{C}$			0.016	0.030
30 $^\circ\text{C}$			0.014	0.025
35 $^\circ\text{C}$			0.012	0.023
40 $^\circ\text{C}$			0.0105	0.0215

TABLE 1 (Continued)

2. Mixtures of sec-Butyl Alcohol (Butan - 2 - Ol) with water to obtain different values of surface tension

Liquid Property	Pure Water	2.44% Butan	6.98% Butan
Density ρ_L in Kg/m^3 @ 20°C	998.2	993.3	984.67
Surface tension σ_L in N/m @ 20°C	0.0736	0.05189	0.03945
Absolute viscosity μ_L in Ns/m^2 @ 20°C	0.001	0.0011	0.00127

TABLE 1 (Continued)

3. Dibromo-ethane (ethylene dibromide) diluted with methylated spirit to obtain a wide range of density.

Liquid Property	Pure Methylated Spirit	50% Dibromo-ethane	60% Dibromo-ethane
Density ρ_L in Kg/m^3 @ 20°C	812	1503	1830
Surface tension σ_L in N/m @ 20°C	0.0262	0.0328	0.0337
Absolute viscosity μ_L in Ns/m^2 @ 20°C	0.00153	0.00159	0.00160

From a fundamental viewpoint, the penetration and break-up behaviour of a discrete liquid jet in a cross flowing airstream would help further our understanding of the mechanics of plain-jet airblast atomization and consequently enable better understanding of the behaviour of a complete atomizer of this type. It is hoped that this will eventually allow improved design procedures for such airblast atomizers in future.

The work reported here is a continuation of that carried out earlier at the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. The first phase of the investigation focused attention upon the influence of airstream velocity, the initial injection velocity of the liquid jet, and the injection orifice diameter. Reference (4) details the results. Since then the work has been extended to include the effects of liquid/orifice-geometry variables and the results are detailed in this paper.

SELECTION OF TEST CONDITIONS

The major variables selected for this second phase of the experimental investigation were: the liquid properties of viscosity, surface tension and density; the angular orientation of the injection orifice and the length-to-diameter (L/d) ratio of the injection orifice. Consequently, the effect of airstream density was left for the subsequent phase.

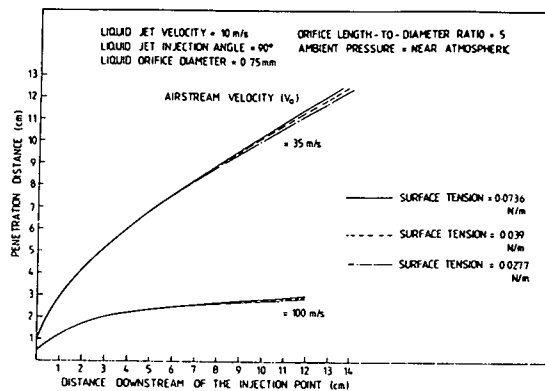


FIG 2 EFFECT OF LIQUID SURFACE TENSION ON THE EXPERIMENTAL PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

The approximate ranges of variables actually covered in the experiments are detailed below:

Airstream velocity	35 to 150 m/s
Airstream density	not varied (i.e. that corresponding to normal atmospheric pressure and temperature conditions)
Liquid jet velocity	5 to 25 m/s
Liquid viscosity	0.001 to 0.125 $\frac{\text{Ns}}{\text{m}^2}$
Liquid surface tension	0.027 to 0.074 $\frac{\text{N}}{\text{m}}$
Liquid density	812 to 1830 $\frac{\text{kg}}{\text{m}^3}$
Injection orifice diameter	0.75 to 2.55 mm
Injection orifice L/D ratio	5 to 14
Angular orientation of the injection orifice	30 to 90 degrees (from horizontal)

EXPERIMENTAL DETAILS

The experimental rig used to study the liquid-jet penetration and break-up is shown in Fig.1 and described in detail in (4). Air at near normal atmospheric pressure and temperature was supplied to a transparent test section (12.5cm x 12.5cm square and 34cm long) through a bellmouth located in the settling chamber.

Water was fed to the plain-jet injector, mounted flush to the inside surface of the test section, from a multi-stage pump, while the other liquids were supplied from reservoirs pressurized with nitrogen. All liquids were supplied through a bank of precision flowmeters appropriately calibrated for each different liquid at the relevant working temperature.

In order to de-couple and examine the independent effects of the various liquid properties upon penetration and break-up, it was necessary to prepare special liquid solutions featuring a controlled

variation of one liquid property at a time. For instance, to study the separate effect of viscosity upon droplet size and jet penetration, a number of different liquid solutions were prepared, each with substantially the same values of surface tension and density but with markedly different values of viscosity. In a similar manner two other sets of liquids were prepared - one to allow controlled variation of surface tension alone and the second for controlled variation of density alone. Standard laboratory techniques were used to obtain the liquid viscosity, surface tension and density data and these values are given in Table 1.

The penetration profiles were determined through the use of wide-view still photography while the droplet size measurements were made using the well-established laser light-scattering technique. This optical technique, an extension of that developed by Dobbins et al (5), is based upon the principles of forward diffractive scattering of a parallel monochromatic beam of light as it passes through the test spray. This technique does not interfere with the spray and gives reasonably accurate assessment of SMD (down to 20 microns). Both these techniques were used in the earlier investigation outlined in Ref.(4) and have been found to be accurate to within about 10 - 15 percent.

RESULTS

Jet Penetration Model

The jet penetration model developed in Ref.(4), comprises a pre- and a post-disintegration regime separated by a break-up parameter. The liquid jet is considered to remain collimated during the short distance pre-disintegration regime. Beyond this, the interaction with the prevailing airstream sets up instabilities in the liquid jet and consequently the jet cross-section becomes distorted and the jet disintegrates rapidly to yield ligaments initially, and drops subsequently. The resulting droplet trajectories are determined by the prevailing flow-field.

The predictions of this penetration model were tested in Ref.(4) against the experimental data relating only to a limited set of variables - those covering liquid jet/airstream velocity and the injection orifice diameter. Consequently, how the predictions of this penetration model would compare against experimental data covering other variables was not known, thus somewhat restricting the usefulness / applicability of the model. The equations of motion developed in Ref.(4) for the pre- and post-disintegration regimes as well as the break-up parameter were used in their existing form to predict the penetration profiles for the extended set of variables featured in this study - those encompassing the density, surface tension and viscosity of the injectant; the angular orientation as well as the length-to-diameter ratio of the injection orifice, etc. The level of agreement realised with the experimental penetration profiles was considered satisfactory and is discussed in a subsequent section of this paper.

Jet Penetration Experimental

Figures 2 and 3 illustrate the effect of liquid surface tension and viscosity variation upon the experimental penetration characteristics of the liquid jet for two different levels of airstream velocities respectively. It is quite clear that a wide variation in these two physical properties has little effect upon the penetration behaviour of the liquid jet.

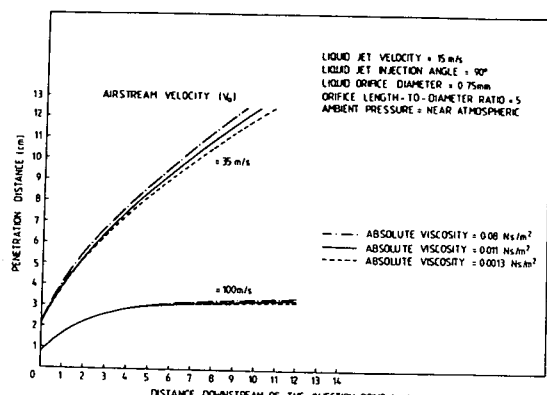


FIG. 3 EFFECT OF LIQUID VISCOSITY ON THE EXPERIMENTAL PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

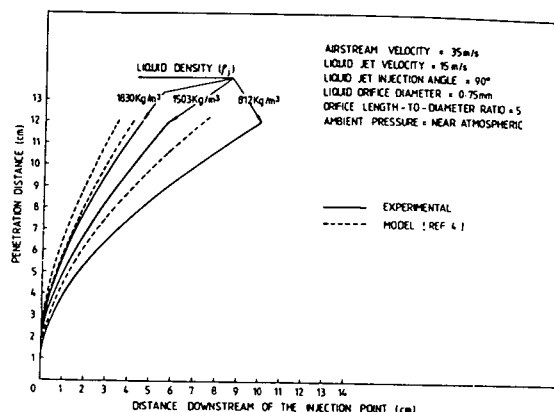


FIG. 4 EFFECT OF LIQUID DENSITY ON THE PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

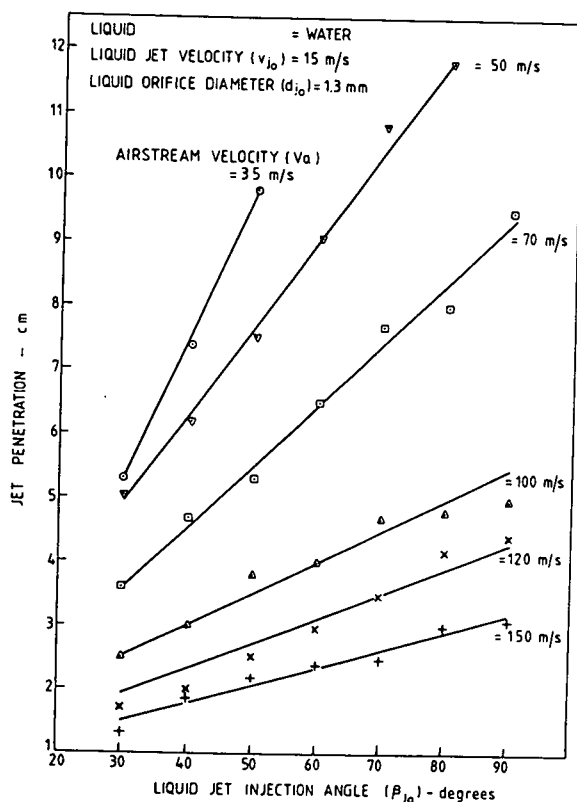


FIG. 5 VARIATION OF PENETRATION WITH THE LIQUID JET INJECTION ANGLE FOR DIFFERENT AIRSTREAM VELOCITIES

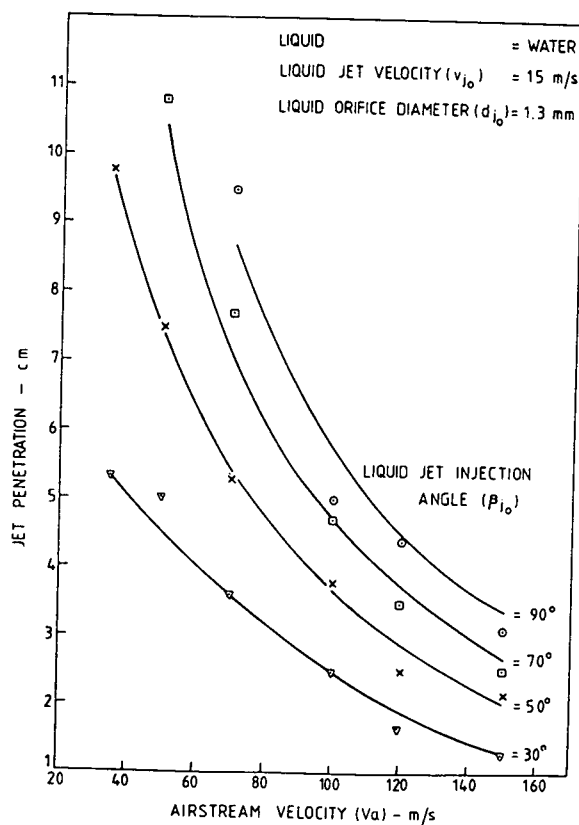


FIG. 6 VARIATION OF PENETRATION WITH AIRSTREAM VELOCITY FOR DIFFERENT LIQUID JET INJECTION ANGLES

The influence of liquid density upon jet penetration is depicted in Fig. 4. As can be seen, the effect of liquid density is in noticeable contrast with that of viscosity and surface tension. The noticeable influence exerted by liquid density variation upon penetration is not surprising due to the dependence of the jet momentum upon its density.

Fig. 5 illustrates the effect of liquid jet injection angle upon penetration characteristics for a wide range of airstream velocities. Clearly the

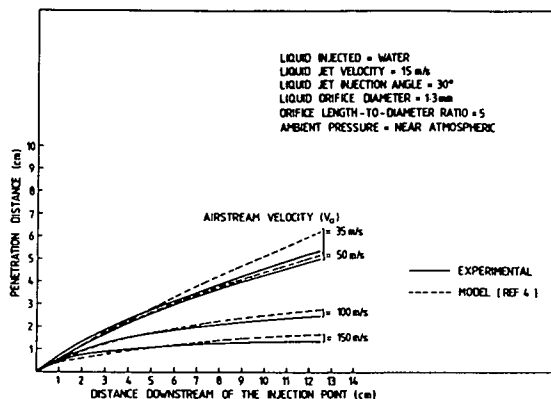


FIG. 7 EFFECT OF AIRSTREAM VELOCITY ON THE PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

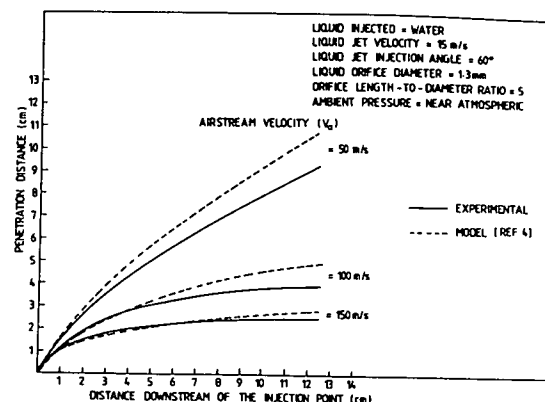


FIG. 8 EFFECT OF AIRSTREAM VELOCITY ON THE PENETRATION CHARACTERISTICS OF A DISCRETE LIQUID JET

liquid jet penetration increases with an increase in the injection angle for the entire range of airstream velocities investigated here, though to a lesser extent for higher air velocities. The data of Fig. 5 has been cross-plotted in Fig. 6 to illustrate the liquid jet penetration - airstream velocity interrelation for a range of injection angles. It should be pointed out here that in Figures 5 and 6 penetration was arbitrarily chosen to indicate the distance (along the Y-axis) of the outer visible boundary of the liquid jet at a station some 12 centimetres (along the X-axis) from the injection point. This approach was retained from phase one (4).

Orifice length-to-diameter ratio variation within the 5 to 14 range was observed to exhibit very little influence upon the jet penetration.

Comparison of the Experimental Penetration Data with the Model

The experimental penetration profiles discussed above were compared with the predictions of the model developed in this research program and outlined in detail in Ref. (4). Figures 4, 7 and 8 illustrate the level of agreement achieved. The model predictions were observed to be within about 20 percent of the entire experimental data collected for wide-ranging air / liquid / injector variables. This level of agreement is considered satisfactory in view of the possible inaccuracies associated with the liquid / air flow monitoring, the injector manufacturing, etc.

Dropsizes Experimental

The influence of measuring station distance, along the spray axis, upon mean dropsizes was examined in detail in the earlier phase (4). It was concluded that the variation of spray sampling distance beyond 5 centimetres had no measurable influence upon the mean dropsizes. Consequently, all the dropsizes data reported in this paper was obtained at a distance of 5 centimetres from the injection point.

Surface tension forces tend to impair atomization quality by opposing any distortion of the liquid surface, thereby delaying the formation of ligaments. This fact is demonstrated quantitatively in Figures 9 and 10 for a range of airstream/liquid jet velocities.

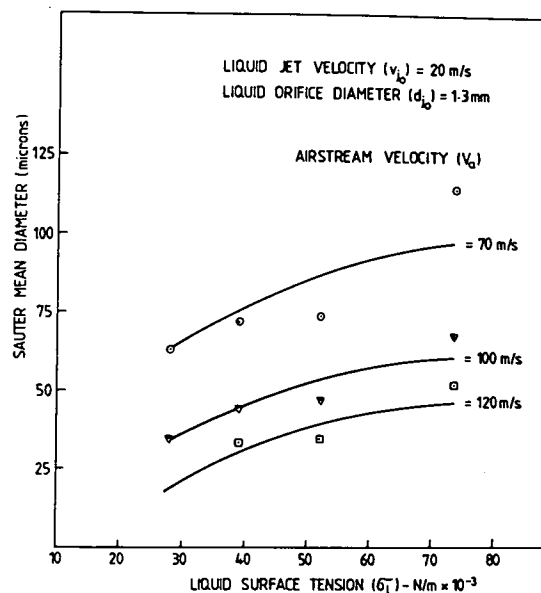


FIG. 9 VARIATION OF MEAN DROPSIZES WITH LIQUID SURFACE TENSION

Clearly an increase in liquid surface tension has an adverse influence upon the spray mean dropsizes performance.

In general, viscosity forces tend to oppose the disintegration of ligaments into drops and to resist the further breaking up of drops already formed. This adverse effect of viscosity on atomization quality is shown in Fig. 11 in which SMD is plotted against liquid viscosity for various levels of airstream velocities. This figure also demonstrates the well known beneficial effect of an increase in airstream velocity upon spray mean dropsizes.

Figure 12 illustrates the effect of varying the liquid orifice diameter upon dropsizes for a high viscosity spray medium. Clearly an increase in the diameter of the injector orifice has an adverse impact upon the atomization performance for the entire range of airstream velocities tested here.

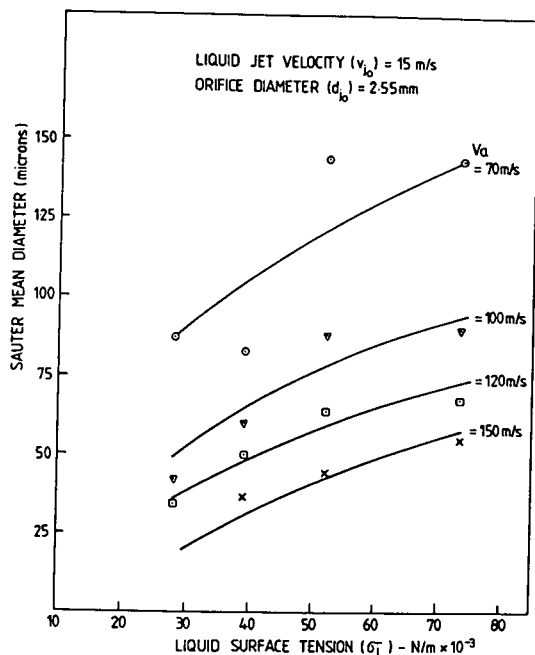


FIG. 10 VARIATION OF MEAN DROPSIZE WITH LIQUID SURFACE TENSION FOR VARIOUS LEVELS OF AIRSTREAM VELOCITY

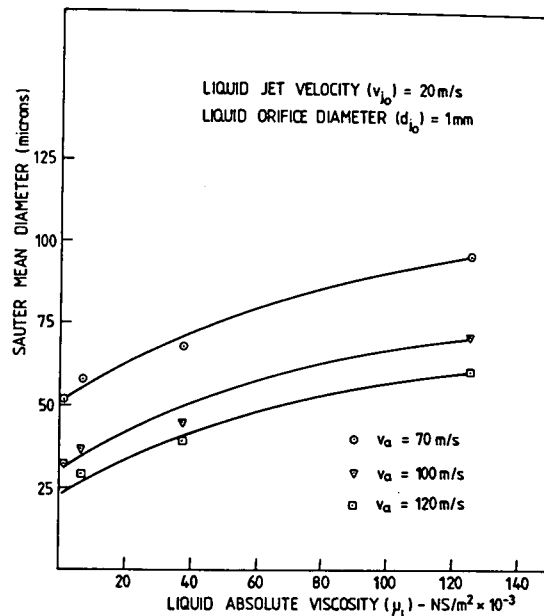


FIG. 11 VARIATION OF MEAN DROPSIZE WITH LIQUID VISCOSITY FOR VARIOUS LEVELS OF AIRSTREAM VELOCITY

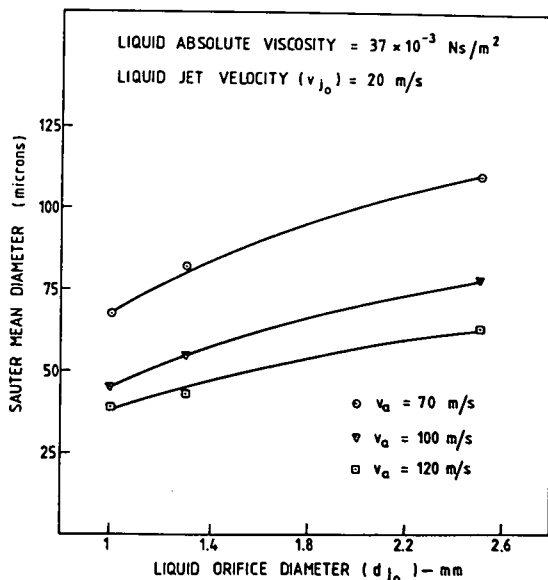


FIG. 12 LIQUID ORIFICE SCALE EFFECT AT HIGH VISCOSITY

The influence of varying the liquid jet injection angle upon mean dropsize for a range of airstream velocities is illustrated in Fig.13. These results,

whilst confirming the beneficial effect of increased airstream velocity, show that an increase in injection angle yields an improvement in spray fineness. As can be seen from this figure the cross-flow case, i.e. a jet injection angle of 90° to the airstream, results in minimum mean dropsize. Another noteworthy feature here is the relatively flat nature of curves for injection angles between about 60° to 90° degrees, especially for the low airstream velocity regime.

The influence, upon spray mean dropsize, of orifice length-to-diameter ratio variation within the 5 to 14 range was observed to be relatively insignificant.

Analysis of Dropsizes Data

Systematic evaluation of the low-viscosity experimental data revealed them to correlate satisfactorily with an equation of the following form :

$$SMD \propto \frac{\sigma_l^{0.6}}{V_a^{1.2}} d_{j0}^{0.4} \quad (1)$$

Examination of the high-viscosity dropsizes data indicated that the liquid viscosity influence was apparently somewhat independent of the airstream velocity, thus implying that to the right hand side of the "Eq.(1)" above should be added another term to take into account the effect of liquid viscosity upon SMD. The analysis of the high-viscosity data led to the development of the following equation :

$$SMD = A_1 \left(\frac{\sigma_l^{0.6}}{V_a^{1.2}} \right) d_{j0}^{0.4} + B_1 \left(\frac{\mu_l^2}{\sigma_l \rho_l} \right)^{0.45} d_{j0}^{0.55} \quad (2)$$

It can be readily seen that "Eq.(2)" above is not

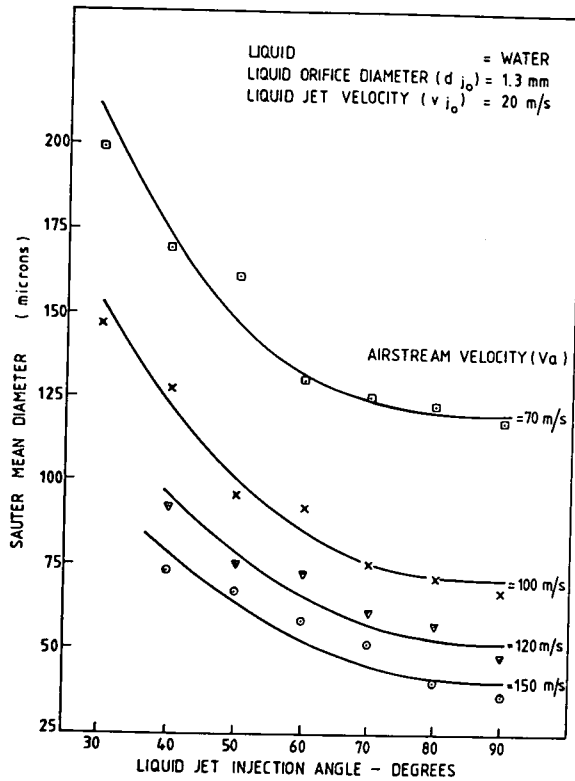


FIG. 13 VARIATION OF SMD WITH THE ANGLE OF INJECTION FOR VARIOUS AIRSTREAM VELOCITY LEVELS

dimensionally consistent and consequently A_1 and B_1 are not dimensionless constants. However, it can be made dimensionally consistent by introducing the air density term as given below :

$$SMD = A \left(\frac{\sigma_l}{\rho_a v_a^2} \right)^{0.6} d_{jo}^{0.4} + B \left(\frac{\mu_l^2}{\sigma_l \rho_l} \right)^{0.45} d_{jo}^{0.55} \quad (3)$$

or in the dimensionless form as :

$$\frac{SMD}{d_{jo}} = A \left(\frac{1}{W_{e,a}} \right)^{0.6} + B \left(\frac{W_{e,l}}{Re^2} \right)^{0.45} \quad (4)$$

where A , B are dimensionless constants

$$W_{e,a} = \text{airstream Weber number, i.e.} \quad \frac{\rho_a v_a^2 d_{jo}}{\sigma_l}$$

$$W_{e,l} = \text{liquid jet Weber number, i.e.} \quad \frac{\rho_l v_{jo}^2 d_{jo}}{\sigma_l}$$

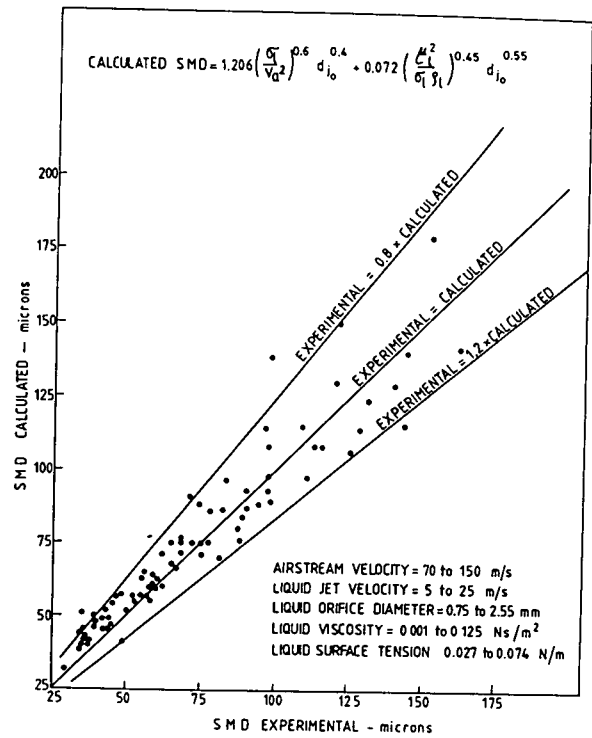


FIG. 14 COMPARISON OF CALCULATED AND EXPERIMENTAL SMD VALUES

$$Re = \text{Reynolds number, i.e.} \quad \frac{\rho_l v_{jo} d_{jo}}{\mu_l}$$

The correlation outlined in "Eq.(2)" above is preferred because the influence of airstream density has not been experimentally examined in this investigation. It is recognised here, that further work will be required to cover this in order to extend the accuracy and applicability of the correlation evolved herein. The level of correlation between the experimental data collected in this study with the predictions of "Eq.(2)" above with $A_1 = 1.206$ and $B_1 = 0.072$ is illustrated in Fig.14. Almost the whole of the experimental data can be observed to fall within about ± 20 percent of the predicted values.

It is worth pointing out that the contribution of the viscosity-dominant second term in the SMD correlation evolved herein, increases with an increase in fuel viscosity. This contribution changes from that of insignificance for the low-viscosity kerosine fuel to that of increasing significance for the high-viscosity spray medium.

It is clearly of interest to see how the results of this investigation agree with those of previous researchers, notably Ingebo (6) and Weiss and Worsham (7). A common feature of all these studies was the cross-flow injection of liquid jet/jets into a non-swirling, high-velocity airstream. Such a comparison for low-viscosity spray medium (high-viscosity media not having been experimentally examined in (6) and

(7)) reveals the following :

$$SMD \propto V_a^{-1.2}, d_{j0}^{0.2}, \sigma_l^{0.4} \dots \dots \text{(Ref. (6))}$$

$$SMD \propto V_a^{-1.33}, d_{j0}^{0.16}, \sigma_l^{0.41} \dots \dots \text{(Ref. (7))}$$

$$SMD \propto V_a^{-1.2}, d_{j0}^{0.4}, \sigma_l^{0.6} \dots \dots \text{(This study)}$$

The dominating influence of air properties (i.e. velocity as well as density) upon spray mean dropsize for the low-viscosity liquids is now well-established (1, 2). Clearly, the level of agreement between the different exponents for the important air velocity variable is reasonable.

CONCLUSIONS

The main conclusions that can be drawn from this investigation are as follows :-

Jet Penetration

- 1) From amongst the liquid properties of density, surface tension and viscosity, only density exercises noticeable effect upon the penetration behaviour of a liquid jet.
- 2) A reduction in the angle at which the liquid jet is injected relative to airstream, reduces the sensitivity of jet penetration to liquid and air-flow conditions.
- 3) Variation of orifice length-to-diameter ratio appears to have no measurable effect upon jet penetration.
- 4) The predictions of the penetration model, developed in an earlier paper (4), are in reasonable agreement with the experimentally measured penetration profiles.

Break-up

- 5) The Sauter mean diameter performance of a discrete liquid jet injected into a high velocity cross-flowing airstream is predicted with a reasonable degree of accuracy by the following correlation :

$$SMD = 1.206 \left(\frac{\sigma_l}{V_a^2} \right)^{0.6} d_{j0}^{0.4} + 0.072 \left(\frac{u_l^2}{\sigma_l \rho_l} \right)^{0.45} d_{j0}^{0.55}$$

over the following ranges of operating conditions :

Airstream velocity	70 to 150 m/s
Liquid viscosity	0.001 to 0.125 $\frac{Ns}{m^2}$
Liquid surface tension	0.027 to 0.074 $\frac{N}{m}$
Liquid jet velocity	5 to 25 m/s
Liquid orifice diameter	0.75 to 2.55mm

- 6) The contribution of the viscosity-dominated second term in the above equation changes from one of insignificance for the low-viscosity liquids to that of increasing significance for the high-viscosity liquids.

- 7) The variation of the orifice length-to-diameter ratio has no significant effect upon mean dropsize.

- 8) Minimum mean dropsizes are obtained when the liquid jet is injected at right angles (i.e. cross-flow case) to the airstream.

ACKNOWLEDGEMENTS

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EFFECT OF AIR, LIQUID AND INJECTOR GEOMETRY VARIABLES
UPON THE PERFORMANCE OF A PLAIN-JET AIRBLAST ATOMIZER

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Abstract

The break-up characteristics of a discrete liquid jet injected into a high velocity, cross-flowing, airstream were examined as a basis of plain-jet airblast atomizer design. The main variables covered in this investigation were, airstream velocity (from about 70 to 150 m/s), liquid jet velocity (from about 5 to 25 m/s), injection orifice diameter (from about 0.75 to 1.8 mm), liquid viscosity (from about 0.001 to 0.125 Ns/m²) and liquid surface tension (from about 0.027 to 0.074 N/m). These tests were carried out under normal atmospheric pressure and temperature conditions using a well-established laser light scattering technique for mean dropsize determination. The analysis of the experimental mean dropsize data collected in this study leads to the development of the following correlation.

$$SMD = 0.703 \left(\frac{\sigma_L d_{jo}}{V_a^2} \right)^{0.5} + 0.040 \left(\frac{V_L^2}{\sigma_L \rho_L} \right)^{0.45} d_{jo}^{0.55}$$

Nomenclature

d	Diameter, m
l	Orifice length, m
Re	Reynolds Number
SMD	Sauter Mean Diameter, meter
V	Mean Velocity, m/s
We	Weber Number
μ	Absolute viscosity, Ns/m ²
σ	Surface tension, N/m

Subscripts

a	Air
j	Liquid jet
L	Liquid
o	Injection orifice

1. Introduction

It is widely recognised that the combustion-pollution performance of gas turbine combustors is strongly related to the quality of fuel preparation. In particular, the influence of atomization/vaporization performance upon such combustion characteristics as ignition (both sea level as well as altitude relight), efficiency and stability, temperature traverse quality, levels of flame radiation and the associated wall temperatures, etc, is well-established. In light of this, the detailed atomization performance characteristics of a variety of gas turbine fuel injection systems, especially when operating on the highly refined aviation fuels, have been the subject of numerous investigations over the years. The quality of atomization, as indicated by the sizes of the drops produced by a

given injector as a result of the fuel disintegration, has been the main feature under examination in a great many of these investigations in order to relate it to the injector design/operating conditions as well as the fuel properties.

From a fundamental viewpoint, all that is required to atomize the liquid fuel is the existence of a relative velocity between the liquid and its surrounding environment (gas or air). Generally, the higher the relative velocity the stronger the disintegrating forces and consequently the finer the resulting drops. In the conventional "pressure" atomizers, high velocity is imparted to the liquid fuel by discharging it under pressure through a fine orifice into a relatively stagnant air zone. An alternative approach is to inject liquid at a relatively low velocity (and hence low pressure) into a high velocity airstream. Probably, the most common gas turbine type of fuel injector based upon this high velocity airstream concept is the so called "airblast" atomizer.

The superior combustion-pollution performance of the airblast atomizer has, in recent times, become increasingly apparent, leading to its widespread adoption in the modern, high-pressure ratio aircraft type of gas turbine engine. The airblast atomizer spray is finer in character, and this, combined with the intimate mixing of fuel and air achieved as an integral part of the atomization process, yields a flame with low levels of luminosity and soot, resulting in relatively cooler liner walls and a minimum of exhaust smoke. Another useful asset of the airblast system is that the fuel placement in the primary combustion zone is dictated mainly by the airflow pattern - being almost insensitive to the fuel flow variations. As a consequence, airblast atomizers offer an important practical advantage from the viewpoint of nozzle guide vane/turbine blade life development in that the outlet temperature profile of the combustor efflux gases is sensibly constant under all operating conditions and consequently may be predicted satisfactorily from experiments conducted at convenient operating conditions, as for example lower levels of combustor pressure.

Most of the gas turbines feature airblast atomizers of the "pre-filming" type, wherein the fuel is first spread into a thin, continuous sheet that is sandwiched between two high velocity airstreams in order to achieve minimum drop sizes through high rates of shear.⁽¹⁾ The requirement for two separate high velocity airstreams, tends to somewhat complicate its design. For this reason the "plain-jet" type of airblast atomizer is sometimes preferred. In the plain-jet arrangement, the fuel is not pre-filmed into a thin sheet but instead discharged in the form of several discrete jets into a high velocity single airstream. These

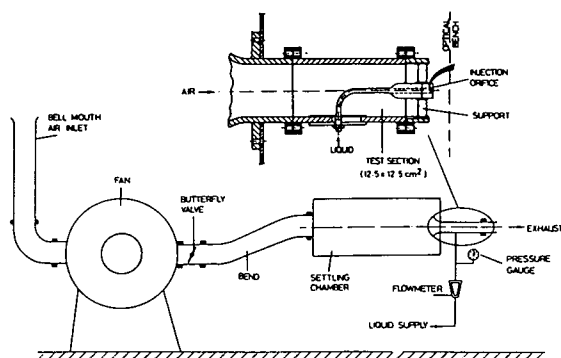


FIG 1 SCHEMATIC DIAGRAM OF TEST RIG

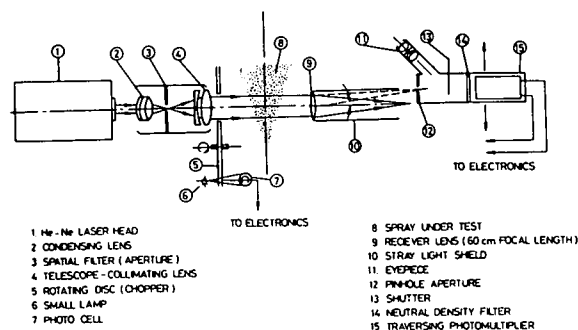


FIG 2 DIAGRAMMATIC FORM OF OPTICAL SYSTEM

discrete jets undergo in-flight disintegration. Much interest has grown in recent times in this plain-jet arrangement as it offers an alternative system of comparable performance and yet is much simpler and cheaper relative to the pre-filming type.⁽²⁾ However, the geometry of the plain-jet airblast atomizer requires to be optimized, on lines similar to the already optimized pre-filming type, if the available air is to be deployed in the most effective manner in order to achieve the best possible level of atomization.

In addition to the foregoing, it is anticipated that the quality of the future fuels is likely to deteriorate. Consequently, the gas turbine engines will be required to be more fuel flexible than before and be capable of satisfactory operation on petroleum derived fuels with increased levels of aromaticity, carbon-to-hydrogen ratio, viscosity final boiling point, etc. Also, satisfactory utilization of fuels derived from such alternative sources as oil shales, tar sands and coal will have to be catered for in the long range. The need to minimize the adverse impact upon spray quality/evaporation rates (and hence combustion performance) from such a fuel quality degradation, therefore, becomes clearly evident.

The work reported here is a part of the continuing airblast atomization research at the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. References (1) and (2) detail the atomization performance characteristics under atmospheric and high pressure conditions respectively, of the earlier investigations into the behaviour of a plain-jet airblast atomizer whose geometry had not been optimized. The purpose of this paper is to present the drops size data collected for a jet of fuel disintegrating in a high velocity airstream as a basis of plain-jet airblast atomization.

2. The Experimental Programme

The major variables selected for this phase of investigation were: the airstream velocity, injection velocity of the liquid jet, injection orifice diameter, and the liquid properties of absolute viscosity and surface tension. Consequently, the effect of the other major variables such as airstream density, liquid density, the angular orientation of the injection orifice, etc., was left for the subsequent phases. This choice was based upon considerations of cost and complexity.

The approximate range of conditions actually covered in the experiments are detailed below :

Airstream velocity	From about 70 to 150 m/s
Airstream density	Not varied (i.e. corresponding to normal atmospheric pressure and temperature conditions)
Liquid jet velocity	From about 5 to 25 m/s
Injection orifice diameter	From about 0.75 to 1.8 mm
Injection orifice l/d ratio	Not varied (i.e. = 4 throughout)
Angular orientation of injection orifice.	Not varied (i.e. at right angle to the airstream)
Liquid viscosity	From about 0.001 to 0.125 Ns/m^2
Liquid surface tension	From about 0.027 to 0.074 N/m

3. Experimental Details

A schematic diagram of the test facility is shown in Fig.1. Air at near normal atmospheric pressure and temperature was supplied to a transparent test section (12.5 cm x 12.5 cm square) through a bellmouth located in the settling chamber. The air mass flow was measured in accordance with BS 1042. Provision was made for the measurement of air temperature and velocity profile in the test section through the use of a thermometer and a total head probe.

Water was fed to the plain-jet injector from a multi-stage pump, while the other liquids were supplied from reservoirs pressurized with nitrogen. All liquids were supplied through a bank of precision flowmeters appropriately calibrated for each different liquid at the relevant working temperature.

In order to de-couple and examine the independent effects of the various liquid properties upon mean drops size, it was necessary to prepare special liquid solutions featuring a controlled

TABLE 1

PHYSICAL PROPERTIES OF TEST LIQUIDS

1. Gas oil and solution of the synthetic hydrocarbon polymer, Hyvis Polybutene No. 05 in kerosine to obtain a wide range of viscosity

Liquid Property	Kerosine	Gas Oil	Hyvis 70%	Hyvis 85%
Density ρ_L in kg/m^3 at 20°C	784	846	823	832
Surface tension σ_L in N/m at 20°C	0.0277	0.0299	0.03008	0.03027
Absolute Viscosity μ_L in Ns/m^2 at 15°C	0.0013	0.0053	0.027	0.072
			0.0205	0.052
		0.0040	0.016	0.030
			0.014	0.025
		0.0031	0.012	0.023
			0.0105	0.0215

TABLE 1 (Continued)

2. Mixtures of sec-Butyl Alcohol (Butan-2-01) with water to obtain different values of surface tension

Liquid Property	Pure Water	2.44% Butan	6.98% Butan
Density ρ_L in kg/m^3 at 20°C	998.2	993.3	984.67
Surface tension σ_L in N/m at 20°C	0.0736	0.05189	0.03945
Absolute viscosity μ_L in Ns/m^2 at 20°C	0.001	0.0011	0.00127

variation of one liquid property at a time. For instance, to study the separate effect of viscosity upon droplet size, a number of different liquid solutions were prepared, each with substantially the same values of surface tension and density but with markedly different values of viscosity. In a similar manner another set of liquids was prepared to allow controlled variation of surface tension alone. Standard laboratory techniques were used to obtain the liquid viscosity and surface tension data and these values are given in Table 1.

The spray Sauter Mean Diameters were measured using the well-established laser light-scattering technique, an extension of that developed by Dobbins, Crocco and Glassman.⁽³⁾ The method is based upon the forward diffractive scattering of a parallel, monochromatic beam of light as it passes

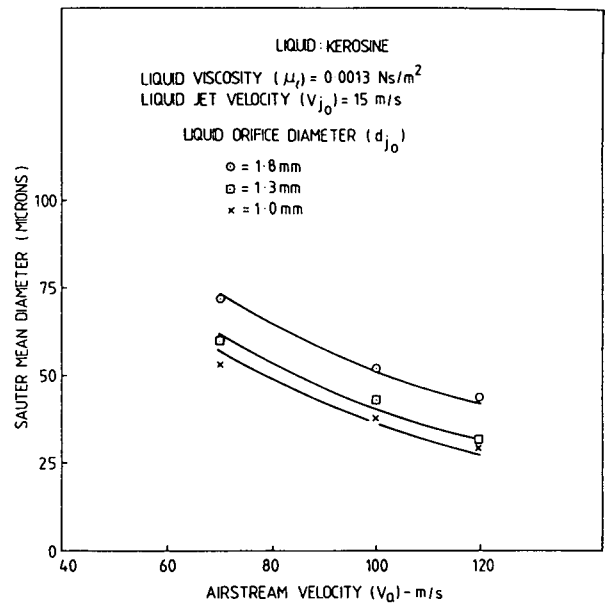


FIG. 3. VARIATION OF SMD WITH AIRSTREAM VELOCITY FOR VARIOUS LIQUID ORIFICE DIAMETERS

through the test spray. Fig. 2 shows the details of the optical system for spray mean droplet size measurement, and its principles and mode of operation are described elsewhere.^(3,4,5) Apart from the rapidity with which data can be obtained, this technique has the advantage that it does not disturb the spray pattern as is the case with all mechanical devices. Recent improvements in the light source as well as optics have enabled spray SMDs of around 20 microns to be measured reasonably accurately.

4. Results and Discussion

Before proceeding with the main investigation concerning the effect of air, liquid and injector geometry variables upon droplet size, it was considered appropriate to examine in detail the influence of measuring station distance, along the spray axis, upon mean droplet size. From the results obtained, it was concluded that the variation of spray sampling distance beyond 5 centimetres had no measurable influence upon the mean droplet size. Consequently, all the droplet size data reported in this paper was obtained at a distance of 5 centimetres downstream of the injection point.

Figs. 3, 4 and 5 illustrate the influence that the airstream velocity exerts upon mean droplet size for a low-viscosity, a high-viscosity and a high surface tension spray media respectively. In each case, an increase in airstream velocity exercises a beneficial influence upon the atomization quality for the entire range of injection orifice diameters investigated.

Surface tension forces tend to impair the spray quality by opposing any distortion of the liquid surface, thereby delaying the formation of ligaments. This fact is demonstrated quantitatively in Fig. 6 for a range of airstream velocities. Clearly

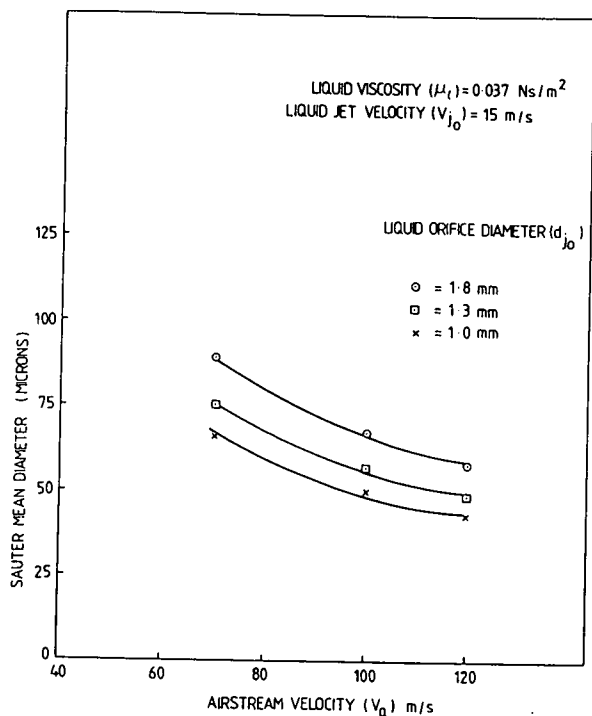


FIG. 4. VARIATION OF SMD WITH AIRSTREAM VELOCITY FOR VARIOUS LIQUID ORIFICE DIAMETERS.

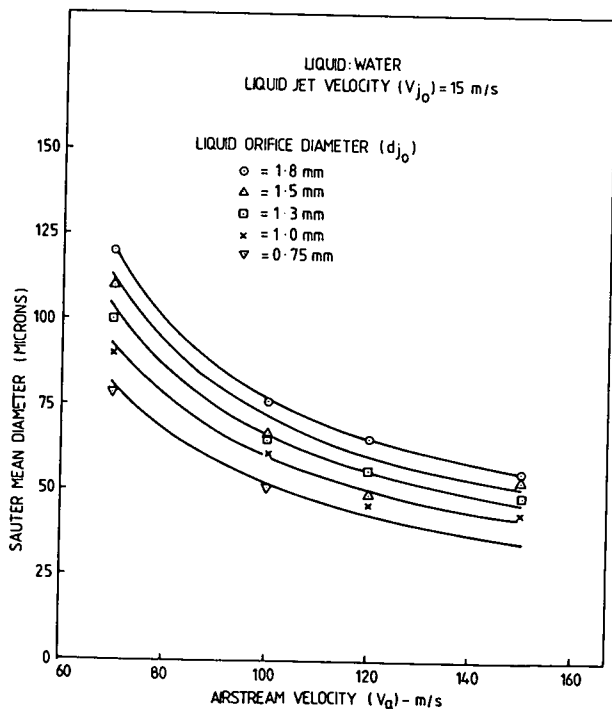


FIG. 5. VARIATION OF SMD WITH AIRSTREAM VELOCITY FOR VARIOUS LIQUID ORIFICE DIAMETERS

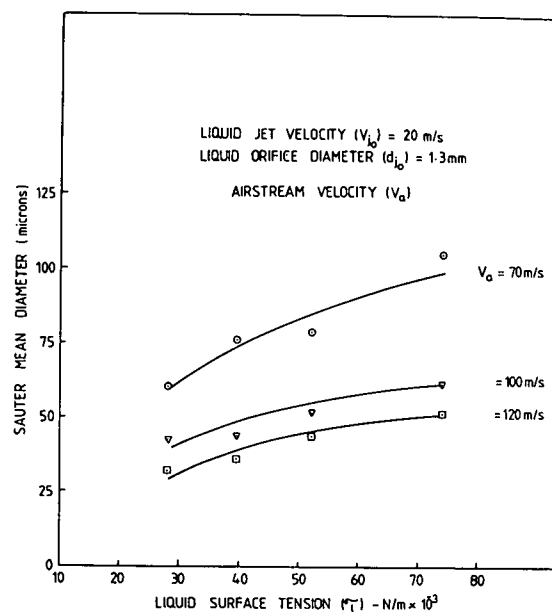


FIG. 6. VARIATION OF MEAN DROP SIZE WITH LIQUID SURFACE TENSION

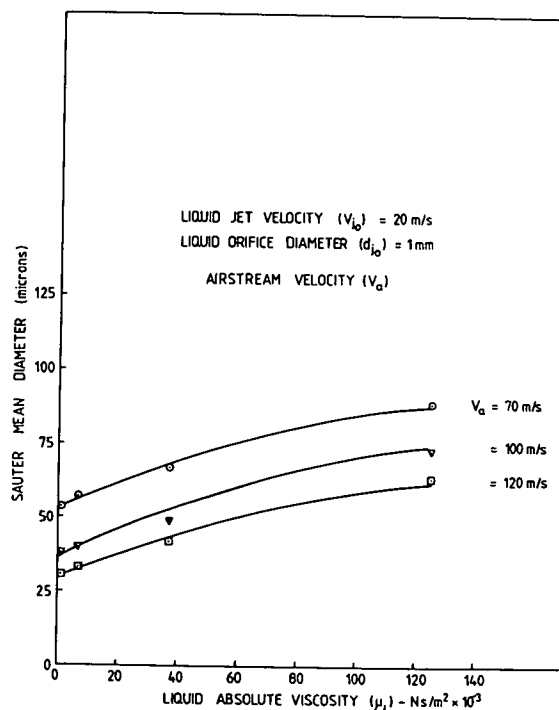


FIG. 7. VARIATION OF MEAN DROP SIZE WITH LIQUID VISCOSITY

an increase in the surface tension of the spray media has an adverse impact upon the mean dropsize.

In general, the viscosity forces tend to oppose the disintegration of ligaments into drops and to resist the further breaking up of drops already formed. This adverse effect of viscosity on atom-

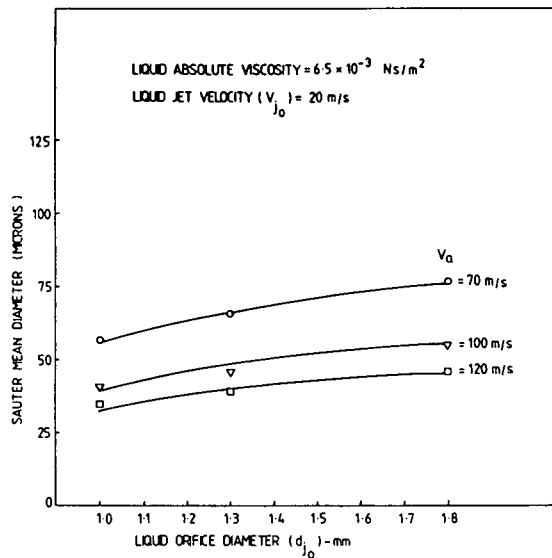


FIG 8 LIQUID ORIFICE SCALE EFFECT FOR LOW VISCOSITY LIQUID

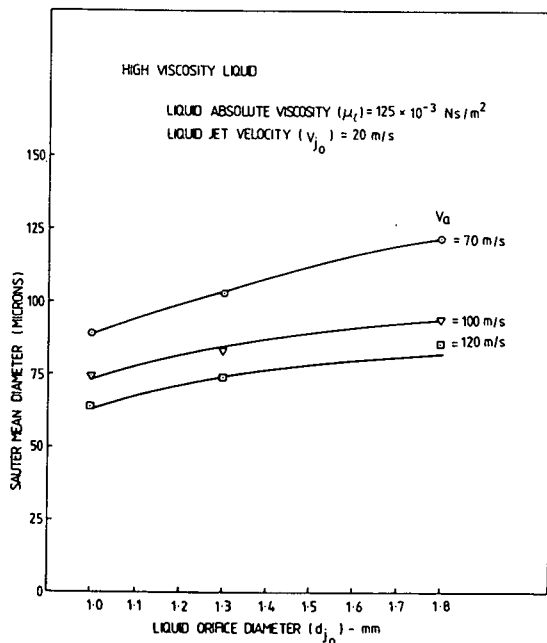


FIG 9 LIQUID ORIFICE SCALE EFFECT FOR HIGH VISCOSITY LIQUID

ization performance is shown in Fig.7 in which SMD is plotted against liquid viscosity for a range of airstream velocities.

Figs. 8 and 9 illustrate the effect of varying the liquid orifice diameter upon drops size for a low and a high-viscosity spray media respectively. In both the instances, an increase in the diameter of the injection orifice can clearly be observed to degrade the atomization quality for the entire range of airstream velocities tested. A close examination of these results indicates the degradation effect to be more pronounced for the high-viscosity liquid.

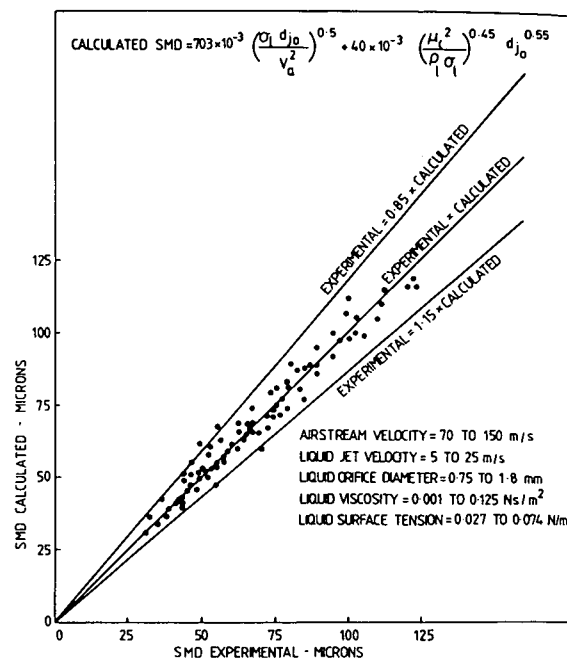


FIG 10 COMPARISON OF CALCULATED AND EXPERIMENTAL SMD VALUES

5. Analysis of Results

Systematic evaluation of the low-viscosity experimental data revealed that a satisfactory correlation could be obtained with an equation of the following form :

$$SMD \propto \frac{(\sigma_L d_{jo})^{0.5}}{V_a} \quad (1)$$

Examination of the high-viscosity mean drops size data indicated that the liquid viscosity influence was apparently somewhat independent of the air-stream velocity, thus implying that to the right hand side of the equation (1) above should be added another term to take into account the effect of liquid viscosity upon SMD. The analysis of the high-viscosity data led to the development of the following equation :

$$SMD = A_1 \frac{(\sigma_L d_{jo})^{0.5}}{V_a} + B_1 \left(\frac{\mu_L^2}{\sigma_L \rho_L} \right)^{0.45} d_{jo}^{0.55} \quad (2)$$

It can be readily seen that equation (2) above is not dimensionally consistent and consequently A_1 and B_1 are not dimensionless constants. However, it can be made dimensionally consistent by introducing the air density term as given below :

$$SMD = A \left(\frac{\sigma_L}{\rho_a V_a^2} \right)^{0.5} d_{jo}^{0.5} + B \left(\frac{\mu_L^2}{\sigma_L \rho_L} \right)^{0.45} d_{jo}^{0.55} \quad (3)$$

or in the dimensionless form as :

$$\frac{SMD}{d_{jo}} = A \left(\frac{1}{W_{e,a}} \right)^{0.5} + B \left(\frac{W_{e,L}}{R_e^2} \right)^{0.45} \quad (4)$$

where A , B are dimensionless constants and

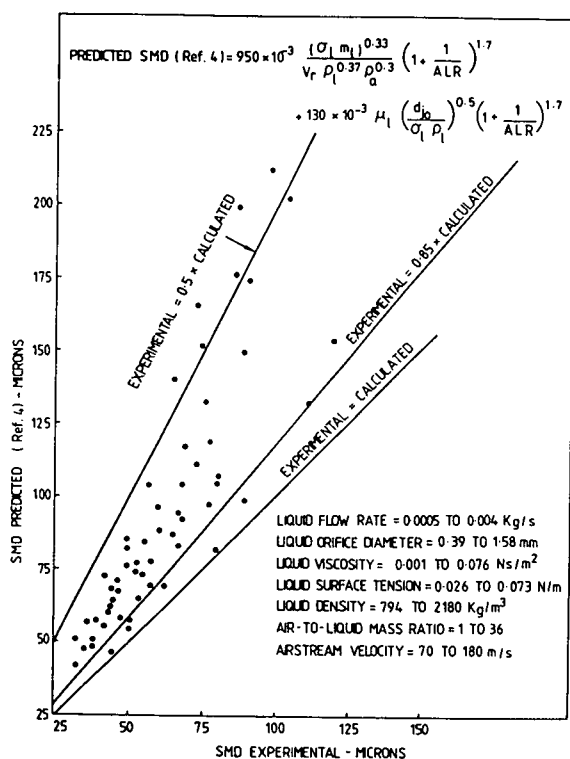


FIG.11. COMPARISON OF MEASURED AND PREDICTED (Ref. 4) VALUES OF SMD

$$W_{e,a} = \text{airstream Weber number, i.e. } \frac{\rho_a V_a^2 d_{jo}}{\sigma_l}$$

$$W_{e,l} = \text{liquid jet Weber number, i.e. } \frac{\rho_l V_{jo}^2 d_{jo}}{\sigma_l}$$

$$R_e = \text{Reynolds number, i.e. } \frac{\rho_l V_{jo} d_{jo}}{\mu_l}$$

The correlation outlined in equation (2) above is preferred because the influence of airstream density has not been experimentally examined in this study. The level of agreement between the experimental data collected in this study with the predictions of equation (2) above with $A_1 = 0.703$ and $B_1 = 0.04$ is illustrated in Fig.10. Almost the whole of the experimental data can be observed to fall within ± 15 percent of the predicted values.

A noteworthy feature of the SMD correlation evolved herein is that the contribution of the viscosity-dominant second term increases with an increase in liquid viscosity. This contribution changes from that of insignificance for the low-viscosity kerosine fuel to that of increasing significance for the high-viscosity spray medium. An important practical implication of this is that the trend towards high-viscosity, lower-grade fuels presents a formidable challenge as regards the attainment of good atomization performance.

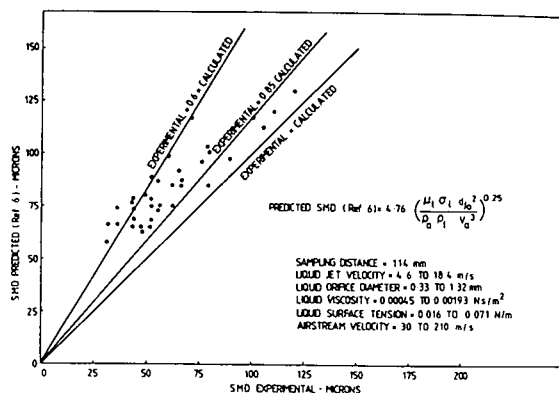


FIG.12. COMPARISON OF MEASURED AND PREDICTED (Ref. 6) VALUES OF SMD (FOR LOW VISCOSITY LIQUIDS)

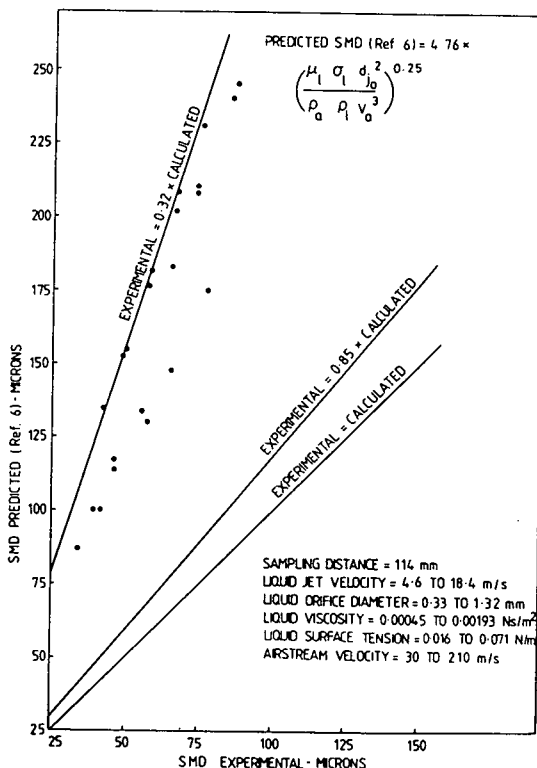


FIG.13. COMPARISON OF MEASURED AND PREDICTED (Ref. 6) VALUES OF SMD (FOR HIGH VISCOSITY LIQUIDS)

6. Comparison with Previous Investigations

It is clearly of interest to see how the findings of this investigation agree with those of previous researchers, notably Jasuja (2), Lorenzetto-Lefebvre (4), Ingebo (6) and Weiss-Worsham (7) respectively.

The correlations developed in the present work agree very closely with those contained in reference 2 except for the term containing the air-to-fuel (liquid) ratio variable. During the current tests, the value of this air-to-fuel ratio variable was consistently high so as to reduce the

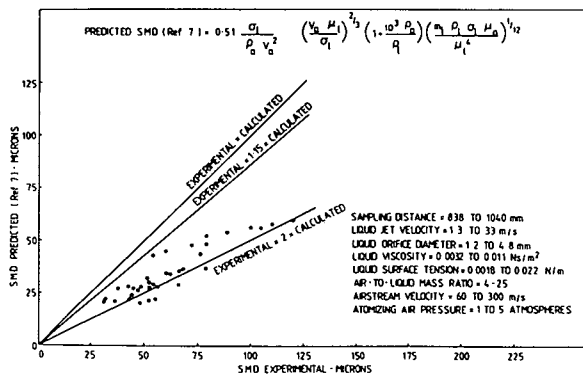


FIG. 14 COMPARISON OF MEASURED AND PREDICTED (REF 7) VALUES OF SMD (FOR LOW-VISCOSITY LIQUIDS)

effective value of $(1 + 1/AFR)$ as unity. A point worth noting here is that the introduction of $\rho_a^{-0.5}$ in the present work, in order to obtain a dimensionally correct SMD correlation (see equation (3) above), is in good agreement with reference 2 wherein the effect of air density upon the droplet performance of a plain-jet airblast atomizer was experimentally examined in some detail.

Fig. 11 illustrates how the experimental data collected in the present work compares against the predictions of correlation outlined in reference 4. Clearly, the level of agreement realised is not satisfactory - in fact the mean droplet sizes predicted by reference 4 are considerably higher than the experimentally measured values. It should be pointed out here that this lack of satisfactory agreement between the two studies is considered to be a result of different liquid injection angles. In the present work, the liquid was injected at right angles (i.e. transverse) to the direction of air, whereas in reference 4 the liquid injection was parallel (i.e. co-axial) to the air flow direction. From this, it would appear that the cross-flow injection of liquid results in more intense air-to-fuel physical contact and consequently leads to better atomization performance.

Predictions of reference 6 are plotted in Figs. 12 and 13 against the experimental values obtained in the present work for low and high-viscosity spray media respectively. As will be seen from these figures, the level of agreement realised is far from satisfactory despite the fact that both these studies featured transverse injection of liquid.

Figs. 14 and 15 illustrate the level of agreement realised between the predictions of reference 7 and the current work for low and high-viscosity liquids respectively. As before, both these studies featured transverse injection of liquid.

The lack of satisfactory agreement for the high-viscosity liquids in both the cases (i.e. references 6 and 7) is not entirely unexpected since both these studies featured low-viscosity media. The reasons for the discrepancy for the low-viscosity liquids are not clear.

7. Conclusions

The main conclusions that can be drawn from this

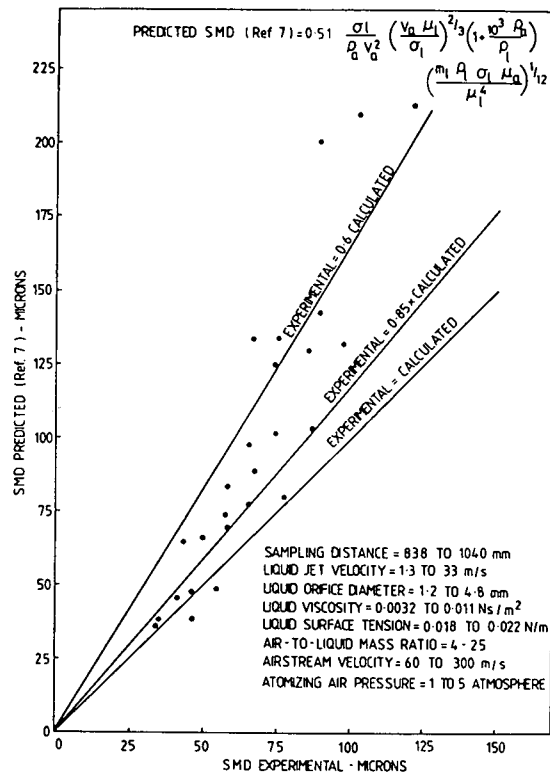


FIG. 15 COMPARISON OF MEASURED AND PREDICTED (REF. 7) VALUES OF SMD (FOR HIGH-VISCOSITY LIQUIDS)

investigation are as follows :

1. From amongst the variables examined, the influence of air velocity upon atomization quality was the most dominant. An improvement in atomization performance being observed with an increase in air velocity.
2. The mean droplet size of the spray increases with an increase in liquid viscosity as well as surface tension.
3. Increasing the diameter of the injection orifice leads to a degradation in atomization performance - the degree of degradation being more pronounced for the high-viscosity liquids.
4. The experimental data on mean droplet size correlate satisfactorily with the equation :

$$SMD = 0.703 \left(\frac{\sigma_L}{\rho_L^2} \right)^{0.5} d_{jo}^{0.5} + 0.04 \left(\frac{\mu_L^2}{\sigma_L \rho_L} \right)^{0.45} d_{jo}^{0.55}$$

over the following ranges of operating conditions :

Airstream velocity	70 to 150 m/s
Liquid viscosity	0.001 to 0.125 Ns/m ²
Liquid surface tension	0.027 to 0.074 N/m
Liquid jet velocity	5 to 25 m/s

Liquid orifice diameter 0.75 to 1.8 mm

8. Acknowledgements

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EFFECTS OF AIRBLAST ATOMIZER DESIGN UPON SPRAY QUALITY

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SUMMARY

This paper reviews the results of numerous investigations that have been conducted on airblast atomization as applied to gas turbine engines. The primary motivation for this is the need to identify the effect that various design features have upon the spray quality so that atomizers of optimum performance can be designed with a minimum of cost and complexity. Attention is focused upon such factors as the atomizer scale, configuration, the nature of fuel preparation before exposure to air, etc, for the most commonly used pre-filming and plain-jet airblast atomizers. The experimental mean drop size data included in this paper has been obtained through the use of well-established laser light-scattering techniques over a wide range of conditions. The general conclusion drawn from the data that is currently available is that the plain-jet airblast atomizers featuring multiple, transversely injected liquid jets into a swirling airstream yield spray quality comparable to that achieved by their pre-filming counterparts especially under high air pressure conditions.

LIST OF SYMBOLS

SMD	=	Sauter Mean Diameter, micron or m
V	=	Velocity, m/s
D, d	=	diameter, m, or mm or cm.
$\frac{\Delta P}{P}$	=	Atomizer air pressure drop, percent
P	=	Pressure, atmosphere
AFR	=	air-to-fuel mass ratio
ALR	=	air-to-liquid mass ratio
ρ	=	density, kg/m ³
σ	=	surface tension, N/m
η	=	absolute viscosity, Ns/m ²
α, β	=	liquid injection angle
γ	=	swirler vane outlet angle
t	=	film thickness (liquid), micron
T	=	temperature, °K

Subscripts

a	=	air
l	=	liquid
o	=	orifice (injection)
p	=	pre-filmer
j	=	jet (liquid)

INTRODUCTION

The quality of fuel preparation is now generally acknowledged to be of considerable importance in many key aspects of gas turbine combustor performance - notably for its influence upon such characteristics as ignition (sea level/altitude relight), efficiency and stability, temperature traverse quality, levels of smoke and other pollutants, levels of flame radiation and the inter-related issue of liner durability. Possible degradation in the quality of the gas turbine fuels is going to require a greater degree of fuel flexibility/multi-fuel capability from the combustors/fuel injectors of the future. Furthermore, the continuing trend towards gas turbines of higher compression ratio requires satisfactory fuel preparation over a far wider range of air pressures/temperatures as well as fuel flows than at present. In addition, there has been, for some time now, pressure to restrict the emission of gas turbine generated exhaust pollutants, and it seems unlikely that this pressure will be significantly relaxed in the near future. The attainment of effective fuel preparation has assumed added importance in order to achieve satisfactory combustion-pollution performance. In the light of this, the detailed performance characteristics of a variety of gas turbine fuel injection systems have been investigated over the years. The quality of atomization, as indicated by the sizes of the drops produced by a given injector following the fuel disintegration, has been the main feature under examination in most of these investigations in order to relate it to the injector design/operating conditions as well as fuel properties.

The superior combustion-pollution performance of the airblast atomizer relative to the conventional pressure atomizer is now well established (Ref.1) and this has led to its widespread adoption in the modern, high-pressure ratio gas turbine. The airblast atomizer spray is finer in character due to the intimate mixing of fuel and air achieved as an integral part of the atomization process. This yields a flame of low luminosity and soot, thus resulting in relatively cooler liner walls and a minimum of exhaust smoke. Furthermore, the placement of the fuel droplets in the burning zone is dictated mainly by the airflow pattern - being almost insensitive to the fuel flow variations. Consequently, airblast atomizers offer an important practical advantage from the viewpoint of nozzle guide vane/turbine blade

life development in that the outlet temperature profile of the combustor efflux gases is sensibly constant under all operating conditions and consequently may be predicted satisfactorily from experiments conducted at convenient operating conditions, such as lower levels of combustor pressure.

From amongst the many diverse geometrical configurations investigated by the different researchers over the years, two specific types of airblast atomizers appear to stand out clearly - namely the pre-filming and the plain-jet types. This is due to the extensive research that they have been subjected to, thus reflecting the interest in them from the gas turbine applications viewpoint. In common with all other forms of airblast atomizers, they utilise high velocity air for the purposes of disintegrating a relatively slow moving liquid stream. There are two main differences between the pre-filming and the plain-jet airblast atomizers. The first one relates to the extent of fuel preparation prior to its exposure to the shearing action of high velocity air, while the second one relates to the air flow passage arrangement/configuration and the intimacy of the resulting fuel and air contact. In the pre-filming arrangement, researched extensively by Lefebvre and his co-workers (2,3), the fuel is first spread into a thin, continuous annular sheet on a surface known as the pre-filming surface before exposure to two high velocity airstreams. Intimate fuel and air contact is achieved by arranging for the two airflows to 'sandwich' the thin fuel sheet. In the plain-jet arrangement, however, the fuel is not pre-filmed into a thin sheet but instead discharged in the form of one or more, discrete, circular jets. These jets of fuel undergo disintegration in-flight in a single airstream, usually provided by a conventional swirler (4). The intimacy of fuel and air contact achieved in this arrangement is related to the swirler/fuel orifice variables.

The purpose of this paper is to outline the present state of knowledge with regard to the fundamental design aspects of airblast atomization, as applied to gas turbines, by bringing together the findings of numerous research studies, especially those conducted during the last decade or so. The primary motivation for this is the need for a thorough understanding of the mechanics of airblast atomization so that atomizers of optimum performance can be designed with a minimum of cost and complexity. Clearly, in a situation of this kind where results have been brought together from a variety of diverse sources, there is the possibility of differences arising with regard to the actual details, for example the use of different drop size measuring techniques, the adoption of different mean drop size definitions, etc. Since this paper is addressing the design aspects of airblast atomizers, special care has been taken to ensure that the comparisons utilised herein are meaningful and valid.

ATOMIZER DETAILS

The conceptual details of the various airblast atomizers included in this study are illustrated in Figure 1. The evolution of the pre-filming type is covered by configurations of Figure 1(a) through to 1(e) with configuration 1(f) being a specially designed, two-dimensional flat sheet, research atomizer of the same family. The different plain-jet configurations that have been investigated are depicted in Figure 1(g) through to 1(k).

Configurations 1(a) and 1(b) show two of the early designs of pre-filming types of atomizers. In configuration 1(a), due to Bennet (5), fuel was given a swirl and made to flow over the face and edge of a disc located in a high velocity airstream. The resulting spray quality, assessed through the coated slide technique, was poor due to the problems of wall-wetting and non-uniform liquid film distribution. Of the four different configurations examined by Lefebvre and Miller (6), the one shown in Figure 1(b) was found to be the best. A swirl chamber, connected to the fuel feed tube through four radial spokes, was used for the purposes of pre-filming the fuel. The swirl chamber featured a shroud to enable the liquid sheet to develop without interference from the airflow. The problems of wall-wetting that had been experienced with the earlier designs had been eliminated by keeping the droplets airborne through the deployment of air on both sides of the fuel film. This 'sandwiching' of the fuel film was also conducive to the attainment of intimate physical contact between the fuel and airstreams, the importance of which from atomization performance viewpoint had previously been highlighted by Gretzinger and Marshall (7). Lefebvre and Miller also recognised the importance of minimising the liquid film thickness as well as that of exposing the liquid film to the shearing action of air on both sides at the point of maximum air velocity.

The configuration of Figure 1(c), featuring a diverging pre-filming arrangement culminating in a sharp lip combined with the somewhat more aerodynamically streamlined air passages (inner as well as outer), was found to yield the best atomization performance from amongst the various different designs studied in Reference 8. The sharp-lipped, diverging pre-filmer geometry was found to be more successful in achieving fuel detachment by centrifugal action. This resulted from the use of swirl slots, introduced in an attempt to obtain an even fuel film, in feeding the fuel on to the pre-filming surface.

This basic sharp edged, diverging pre-filmer geometry was retained in the configuration of Figure 1(d) (Refs.2,3). The main difference between this arrangement and its predecessor relates to the shape of the air passages - those of Figure 1(d) being somewhat more streamlined than of Figure 1(c). Another variant of this pre-filming atomizer family, shown in Figure 1(e), (Ref.9), uses a parallel pre-filming surface with a less sharp lip combined with the deployment of a swirler for the inner as well as the outer airstreams. A somewhat similar 'sandwiching' of the annular fuel sheet between two, swirling airstreams is also discussed in Reference 1. In the main Reference 1 and 9 differ with regard to the shape of the pre-filming surface - a diverging surface in Reference 1 (similar to that of Figure 1(d)) in contrast to the parallel surface of Reference 9.

The atomizer configuration shown in Figure 1(f) is a flat sheet, two-dimensional airblast atomizer that was specially designed by Rizk and Lefebvre (Ref.10) in an attempt to examine the effect of initial liquid film thickness upon atomization quality. The thickness of the liquid film generated by the pre-filming arrangement is, clearly, one of the fundamental features of this type of atomizer and consequently one that needs to be correlated adequately with the mean drop size.

Nukiyama and Tanasawa (ref.11) conducted the first major airblast atomization study using the plain-jet configuration of Figure 1(g). In this arrangement the liquid is injected in the form of a circular jet into a co-axial, co-flowing, high velocity airstream. This form of atomizer has been the subject of several further studies (Refs.12, 13, 14), because of its very simple design. Another simple form of plain-jet atomizer that has been examined in some detail (Refs. 11, 13, 15, 16) comprises the transverse injection of a circular, liquid jet into a high velocity, axial airstream as illustrated in Figure 1(h). The effect of injecting the liquid jet in a direction other than the transverse or co-axial had, up until recently, not been examined. By comparing the data from different atomizers, Rizk and Lefebvre (Ref.17) attempted to identify qualitatively the effect of liquid jet injection angle upon drop size. However, Hussein et al (Ref.18) conducted detailed experiments using the configuration shown in Figure 1(i). The injection angle (β_{jo}) of the circular liquid jet was varied over the 30 to 90 degree range.

The plain-jet atomizer designs discussed so far have comprised the injection of single/multiple liquid jets into a non-swirling airstream. The configuration shown in Figure 1(j), comprising several radially-drilled holes for the injection of liquid in the form of discrete jets into a single high-velocity swirling airstream, was first investigated by Jasuja (Ref.4). This type of atomizer, due to its relatively simple nature (requiring only a swirler and some plain, circular holes), has since been studied in some depth (Refs. 13, 19, 20). The configuration illustrated in Figure 1(k) shows two of the key variables that influence the design and performance of this type of atomizer - notably the swirler geometry and the injection orifice orientation. Hussein (Ref.20) has recently examined in some detail the effect of swirler geometry, particularly the vane type (both straight and curved) and its outlet angle γ , upon the drop size performance. The influence of the liquid orifice orientation, α_o , upon drop size has been studied by Shaw (Ref.21). Clearly, the motivation for optimizing the design of this type of atomizer is the need to deploy the available air in the most effective manner, thus achieving the best possible level of atomization performance. In the arrangement depicted in Figure 1(l), the liquid is injected through several circular holes on to the concave surface of a splash cone located downstream of an air swirler. On emerging from the splash cone, the liquid is picked up by a single, high velocity, swirling airstream. The addition of a splash cone, to what is basically a configuration similar to that of Figure 1(j), has been observed to yield generally poor atomization performance (Refs. 15,22).

EXPERIMENTAL DETAILS

The pre-filming and the plain-jet airblast atomizers have been extensively studied under atmospheric as well as high air pressure conditions at the Cranfield laboratories. A schematic arrangement of the high pressure test facility is shown in Figure 2. The pressure chamber, inside which the atomizer is located, features windows for laser beam access to enable the measurement of the spray SMD. The drop size data, obtained largely at Cranfield, was collected through the use of well-established laser light-scattering techniques. The Cranfield technique, described in Reference 4, is an extension of that developed by Dobbins et al (Ref.23) and is shown schematically in Figure 3. Standard laboratory procedures were adopted for fuel and air mass flow measurements. The test fluids featured in this study are water ($\eta = 0.0010$, $\sigma = 0.0735$, $\rho = 1000$), kerosine ($\eta = 0.0013$, $\sigma = 0.027$, $\rho = 784$), gas oil ($\eta = 0.0053$, $\sigma = 0.0299$, $\rho = 846$) and a 55% residual fuel oil (RFO), 45% gas oil (GO) blend ($\eta = 0.036$ at 30°C working temperature, $\sigma = 0.0331$, $\rho = 913$).

RESULTS

This paper is devoted to a consideration of the effect that various design parameters have upon the airblast atomizer performance and consequently, the effect of operating variables such as the air pressure/temperature, the fuel viscosity, etc, will not be discussed directly. The pre-filming airblast atomizer is examined first, in view of its more widespread usage, followed by the plain-jet type.

Since airblast atomization relies upon the airstream momentum for fuel disintegration, the air-to-fuel (liquid) mass ratio would clearly seem to be an important variable influencing the spray quality. Deficiency of air would result in failure to overcome the viscous/surface tension forces that are resisting liquid disintegration where as an excess of air may result in some of the air not actually participating in the liquid break up due to its physical remoteness. Clearly the size of the air passages (and hence the atomizer bulk/weight) is related to the air mass flow requirement. It has been suggested in Reference 3 that to achieve optimum performance pre-filming atomizers should be designed to operate with an ALR in the 3 to 5 range. Figure 4, taken from Reference 24, shows the effect of atomizer AFR upon SMD for a range of ambient air pressures when using the pre-filming configuration of Figure 1(c). It is clear from this figure that the atomizer AFR effect is relatively weak for air pressures exceeding 3 atmospheres and atomizers designed with an AFR of 2 will give almost as good a drop size performance as atomizers designed with an AFR of 5. Over-sized atomizers are clearly undesirable from air requirement, space, weight and cost considerations.

Engineers are continually faced with the demand to design gas turbine combustors that will operate effectively with a minimum of air pressure drop. This in turn requires careful attention to the detailed aerodynamics of the atomizer air flow passages in order to minimise pressure losses and hence obtain the best possible level of atomization quality. Figure 5 shows the influence that atomizer air pressure drop has upon the spray quality of the pre-filming configuration of Figure 1(a). Clearly, the higher the available air pressure drop, the superior the atomization performance although the degree of this superiority can be seen to diminish somewhat at higher ambient air pressures. The design philosophy behind the configurations (c) and (d) of Figure 1 has been to utilise, as much of the available air pressure drop as is practicable in obtaining the highest possible air velocity in the plane of the pre-filmer lip. An alternative approach (Ref.9) makes use of swirlers, see configuration of Figure 1(e), in the inner as well as the outer air flow passages. The use of swirlers is clearly going to impose additional air pressure drop, but to what extent this is effectively countered through greater intimacy of fuel and air contact and, therefore, better momentum interchange is not evident from the currently available drop size data on the pre-filming atomizer.

The physical scale of the pre-filmer/atomizer is clearly another key design parameter influencing the atomizer performance through its effect upon the thickness of the annular liquid sheet generated at the pre-filming surface. Using the basic configuration of Figure 1(d), El-Shanawany and Lefebvre (Ref.3)

examined the effect of atomizer scale upon mean drop size by conducting tests on three geometrically similar injectors with cross-sectional areas in the ratio of 1:4:16. The results obtained by them, see Figure 6, indicate that a simultaneous increase in the atomizer overall characteristic size as well as the pre-filmer lip diameter D_p has an adverse influence upon the spray quality in accordance with the relationship $SMD \propto D_p^{0.43}$. The influence upon drop size of a change in the pre-filmer lip diameter alone for a given overall characteristic size of atomizer is something which does not appear to have been examined so far. Intuitively, the bigger pre-filmer lip diameter should yield a thinner liquid annular sheet with a possible improvement in atomization performance.

Despite the extensive research on the pre-filming airblast atomizer over the last two decades, very little is known as regards the thickness/evenness of the annular liquid sheet generated by the pre-filming device. This is largely due to the difficulties associated with the measurement of very thin liquid sheets in a complex geometry. The importance of liquid sheet thickness has been recognised for some time now and this prompted Rizk and Lefebvre (Ref.10) to carry out experiments in an attempt to correlate it with the spray mean drop size. They used an atomizer specially designed to deliver two-dimensional, flat, liquid sheets through a discharge slot of known width (see Figure 1(f)). The results obtained by them, shown in Figure 7, confirmed that thin liquid sheets yield lower spray mean drop sizes in accordance with the relationship $SMD \propto t^n$ where n takes the values of 0.4 and 0.55 for low and high viscosity liquids respectively.

The main difference between the plain-jet configurations (g), (h) and (i) of Figure 1 is that relating to the angular orientation of the fuel injection orifice. This in turn is likely to influence the jet trajectory and its interaction with the surrounding air. Figure 8 provides a quantitative insight into the effect of liquid jet injection angle β_{jo} (see Figure 1(i)) upon mean drop size for a range of airstream velocities. As can be seen clearly from this figure the transverse injection case (i.e. $\beta_{jo} = 90^\circ$) results in the smallest mean drop size. In Reference 18, β_{jo} was varied in the 30 to 90 degree range but since the trend is well-established it can be confidently extrapolated to cover the $\beta_{jo} = 0$ case (i.e. the co-axial, co-flowing case). The marked superiority of the transverse liquid injection, relative to the co-axial, co-flowing case was observed by Ingebo (Ref.13) too, and is considered to be a reflection of the more intense air-to-fuel physical contact. This is borne out by the results of Figure 9 wherein the penetration/spatial spread characteristics of the liquid jet are plotted against the injection angle for a range of airstream velocities. In the co-axial, co-flowing case ($\beta_{jo} = 0$) the liquid jet and the airstream are moving parallel to each other and consequently the disintegrating liquid jet is likely to be in contact with the same air streamlines all the time - streamlines that are progressively being depleted of energy. The injection of liquid transverse to the air flow (i.e. $\beta_{jo} = 90^\circ$) gives maximum jet penetration and consequently allows a greater degree of air entrainment which in turn yields a more intimate fuel-to-air interaction. It should be pointed out here that the results shown in Figures 8 and 9 relate to the behaviour of a single jet in a square duct (Ref.18) supplied with a non-swirling airstream (i.e. configuration of Figure 1(i)).

The effect of liquid injection angle for a complete atomizer of the type shown in Figure 1(k) has recently been reported in Reference 21 and a typical set of results is shown in Figure 10. These results indicate that the transverse injection of liquid (i.e. $\alpha_0 = 0^\circ$, note $\alpha_0 = 90^\circ - \beta_{jo}$) from an array of orifices would result in superior spray quality relative to the co-axial, co-flowing case (i.e. $\alpha_0 = 90^\circ$) even in a swirling airstream. Also investigated in this study was the effect of injecting liquid in an upstream direction (i.e. $\alpha_0 = -15^\circ$ and -30°). It seems that the atomization performance can be improved further, especially at low airstream velocities, by utilising the upstream injection configuration.

Many plain-jet atomization research studies have used the size of the fuel injection orifice as the characteristic dimension for the purposes of developing mean drop size correlations. Figure 11 illustrates the adverse influence that an increase in injection orifice size has upon the spray quality for a high-viscosity liquid. Although not reported here, a somewhat similar trend has been established for low-viscosity liquids as well (Ref.16). The available evidence seems to suggest that $SMD \propto d_o^n$ where an average value of n is about 0.5. An additional factor whose influence is inter-related to the size of the liquid orifice, is the velocity at which the liquid is injected into the airstream - smaller orifice size requiring higher injection velocity and viceversa. It is well known that airblast systems operate with low fuel pressures/velocities and an examination of Figure 12 shows that the liquid injection velocity has very little effect upon the resulting mean drop size.

A key component of the atomizer configurations (j), (k) and (l) illustrated in Figure 1 is the air swirler. Although the swirlers have been in use for some time now, their usefulness in promoting more effective atomization quality has not been thoroughly investigated. Indeed it has been suggested that their use may in fact be detrimental to the attainment of good atomization performance. Ingebo (Ref.13) carried out a series of experiments using a 70° blade-angle air swirler and his results for the co-axial, co-flowing and the transverse liquid injection cases are shown in Figures 13 and 14 respectively. They clearly show that the use of an air swirler results in a marked improvement in the spray quality for both the configurations. Further experimental evidence regarding the influence of swirler geometry upon drop size has been recently obtained at Cranfield (Ref.20) as a part of an on-going research programme in plain-jet airblast atomization. The main swirler geometry variables that have been studied relate to the vane shape (straight or curved) and the vane outlet angle γ (see Figure 1(k)). Figure 15 shows a typical velocity profile at the outlet of a 45° curved-vane air swirler obtained with a standard cobra probe. Information of this kind is useful when attempting to optimize the atomizer geometry because it enables the liquid injection orifice to be oriented in a manner that encourages maximum physical contact between the liquid and air. Figure 16 illustrates the effect upon spray quality of an air swirler and its geometry for a transversely injected liquid jet. The mean drop size values are plotted against the experimentally measured axial velocities at the exit of four different air swirler configurations - namely the curved vane type with 30° , 45° and 60° outlet angle and a 30° flat vane type. Also included is the non-swirling air configuration for the purposes of comparison. The use of air swirlers is clearly improving the spray quality - curved vane swirlers facilitating a greater degree of improvement relative to their flat vane counterpart. Furthermore, the 60° outlet angle curved vane configuration is yielding the best atomization performance. What is not evident from this figure is the level of air pressure

drop introduced by the different swirler configurations. From a combustor design viewpoint, clearly that is the constraint within which the use of a swirler for atomization purposes has got to be acceptable. Further examination of the data reveals that to achieve a given swirler exit axial velocity, the higher the curved vane outlet angle the higher the air pressure drop requirement. In other words the 60° curved vane swirler, whilst providing the best spray quality also, introduces the highest air pressure drop. It is also evident from the data that curved vanes introduce less pressure drop relative to the flat ones. It is clear from the foregoing discussion that although the use of a swirler is facilitating an improvement in the spray quality, through a more intimate fuel and air physical contact, its geometry needs to be carefully controlled to ensure its acceptability from the air pressure drop viewpoint.

It is perhaps worth pointing out here that the general trends as regards the effect of atomizer air pressure drop (and atomizer AFR) upon drop size are similar for the plain-jet and the pre-filming types of airblast atomizer.

Comparative Performance of the Two Types of Airblast Atomizers

It is possible to provide a comparative assessment of the pre-filming and the plain-jet airblast atomizers by bringing together the results of some comparable studies. Such a comparison is clearly of interest and value to the combustion engineer involved in atomizer design and performance but must be carried out carefully if variations specific to particular tests and techniques are not to inspire misleading conclusions.

Figure 17 facilitates a comparison under atmospheric pressure conditions between the co-axial, co-flowing plain-jet configuration (of Figure 1(g) investigated by Lorenzetto and Lefebvre (Ref.12) and the pre-filming configuration (of Figure 1(d)) studied by Rizkalla and Lefebvre (Ref.2). On the basis of this evidence the complex atomizer configuration of Figure 1(d) is significantly better than the simple configuration of Figure 1(g). A comparison under widely varying ambient air pressures and fuel viscosities for the pre-filming configuration of Figure 1(c) and the plain-jet configuration of Figure 1(j) was provided by Jasuja (Ref.19). An examination of Figures 18, 19 and 20 reveals that, under nominally comparable operating conditions, there is not a great deal of difference between the mean drop size performance of these two atomizer configurations, especially at higher air pressures for the low-viscosity kerosine/gas oil type of spray medium. A limited amount of comparative drop size data on atomizer configurations 1(d) and 1(j) is contained in References 17 and 25. The general conclusion that can be drawn from this is that the plain-jet configuration 1(j) gives spray quality that is comparable to that achieved from the pre-filming configuration 1(c/d). The comparisons drawn from the work of Lorenzetto and Lefebvre and that of Jasuja are consistent in as much as the transverse injection of liquid in a swirling airstream will be significantly better than the co-axial, co-flowing liquid injection in a non-swirling airstream.

CONCLUSIONS

The two main conclusions to be drawn from the evidence that is currently available are as follows:

1. Despite the extensive research on both the pre-filming and the plain-jet atomizers, there still remain major design features that are worthy of further study. In particular the pre-filming device and the air swirler need to be examined in detail to optimize their geometry.
2. The drop size performance of the relatively simple plain-jet airblast atomizer featuring multiple, transversely injected liquid jets into a swirling airstream is comparable to that of its more widely used pre-filming counterpart especially when operating on low viscosity kerosine/gas oil type of media under high air pressure.

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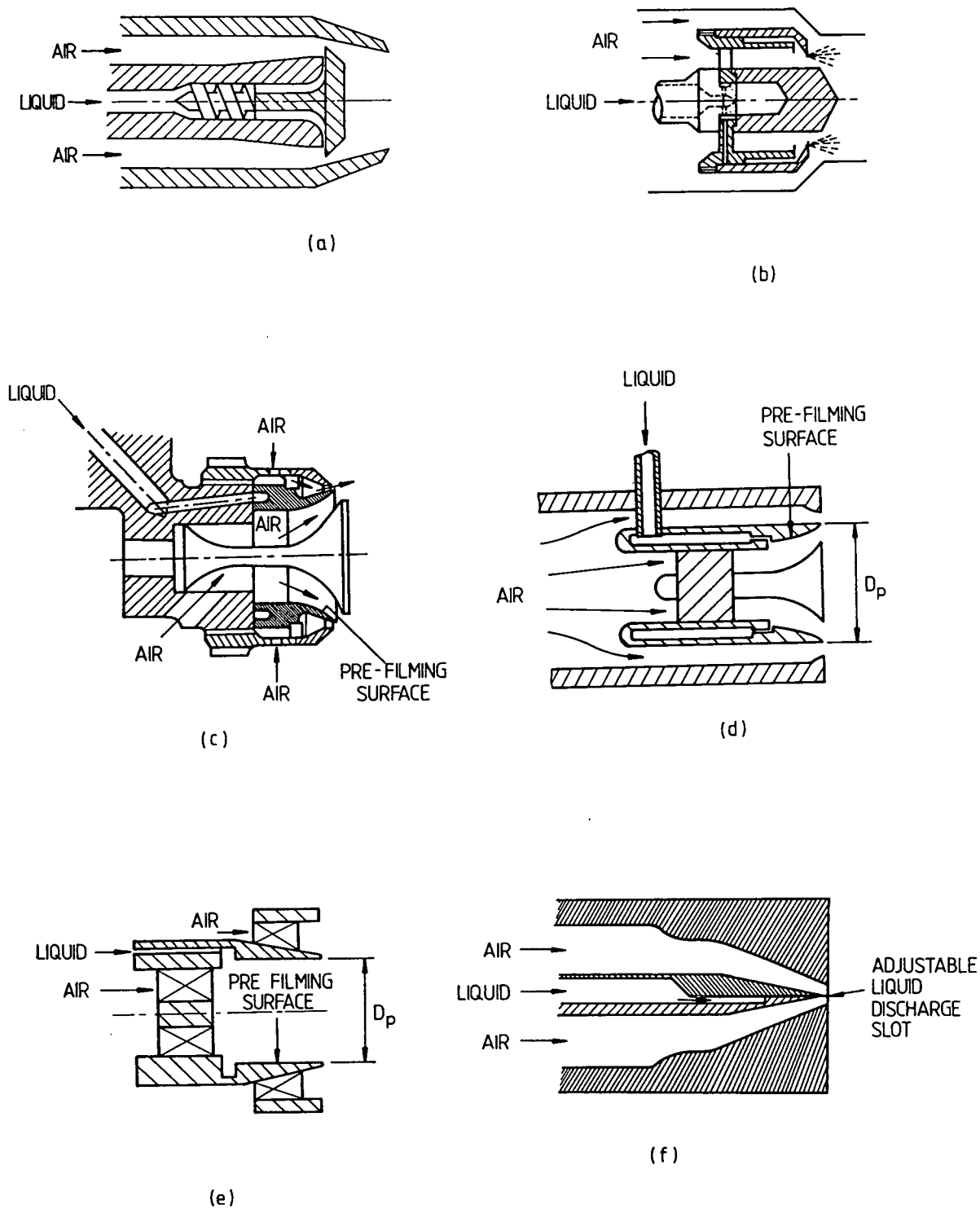
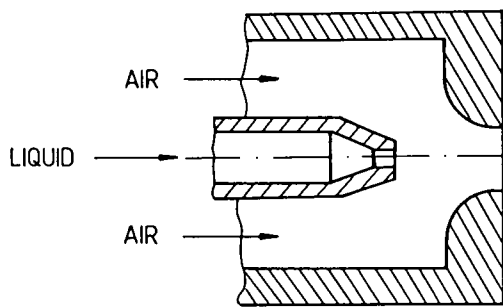
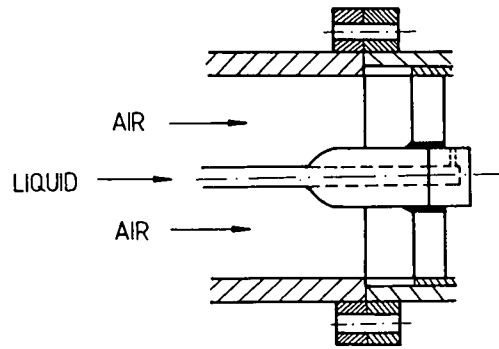


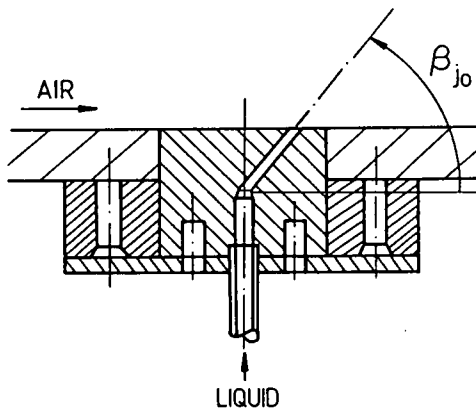
FIG. 1. ATOMIZER CONFIGURATIONS - PRE-FILMING TYPE (1a - 1f)



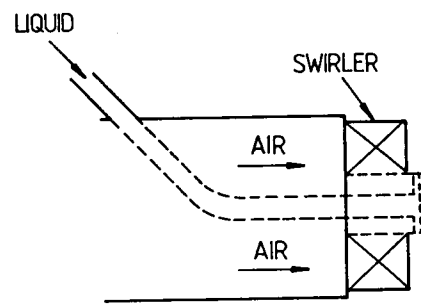
(g)



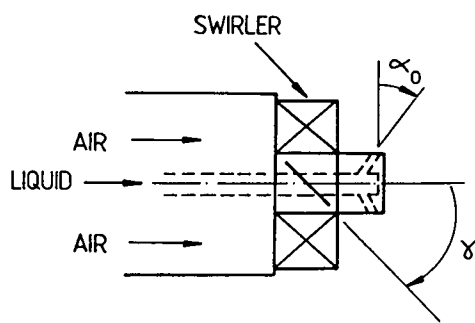
(h)



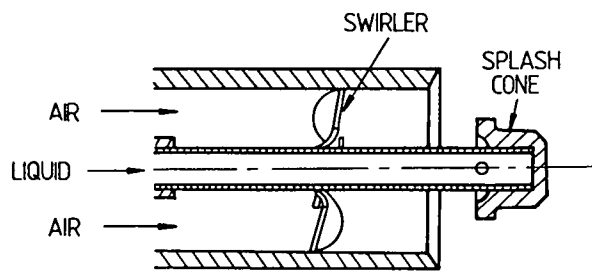
(i)



(j)



(k)



(l)

FIG. 1. ATOMIZER CONFIGURATIONS - PLAIN JET (1g - 1l)

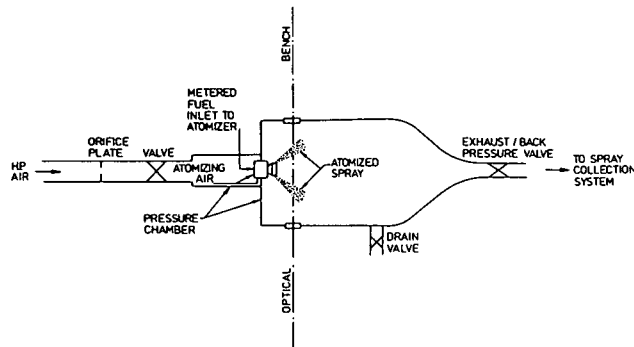


FIG. 2. OUTLINE ARRANGEMENT OF THE TEST INSTALLATION

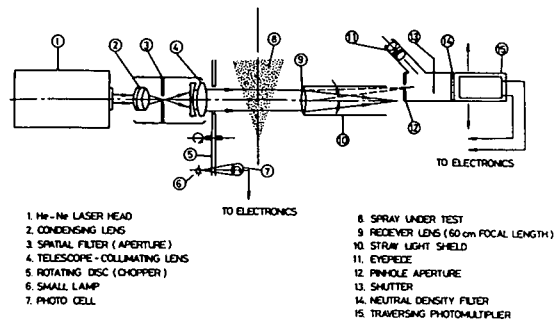


FIG. 3. DIAGRAMMATIC FORM OF OPTICAL SYSTEM.

ATOMIZER AIR PRESSURE DROP = 3.5 PERCENT (NOMINAL)
 SPRAY MEDIUM - R₅₅ BLEND (55% RFO: 45% GO)

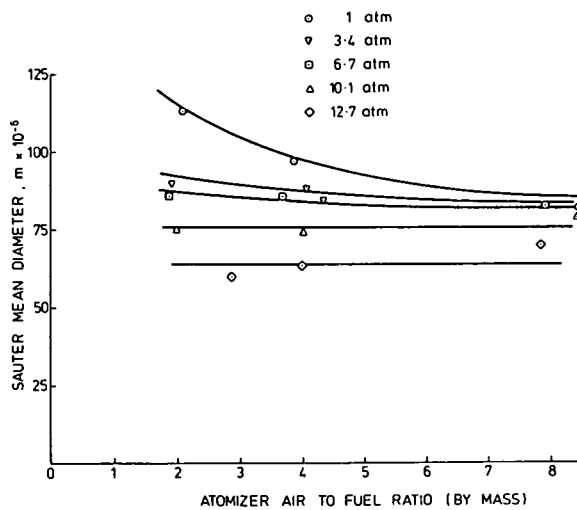


FIG. 4. ATOMIZER MEAN DROPSIZE PERFORMANCE UNDER VARYING AMBIENT AIR UPSTREAM PRESSURE AND AIR TO FUEL RATIO (R₅₅ BLEND)

ATOMIZER AIR TO FUEL RATIO = 4
 SPRAY MEDIUM - KEROSENE

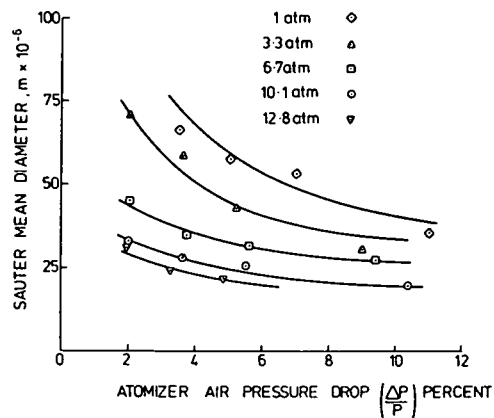


FIG. 5. INFLUENCE OF VARYING ATOMIZER AIR PRESSURE DROP AND AMBIENT AIR UPSTREAM PRESSURE ON SPRAY MEAN DROPSIZE

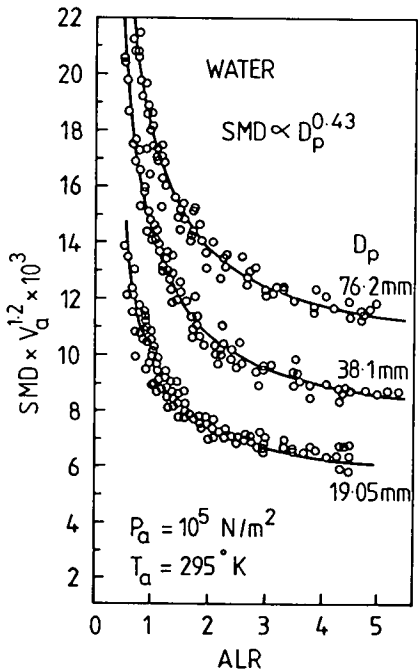


FIG. 6 EFFECT OF ATOMIZER LINEAR SCALE ON MEAN DROP SIZE.³

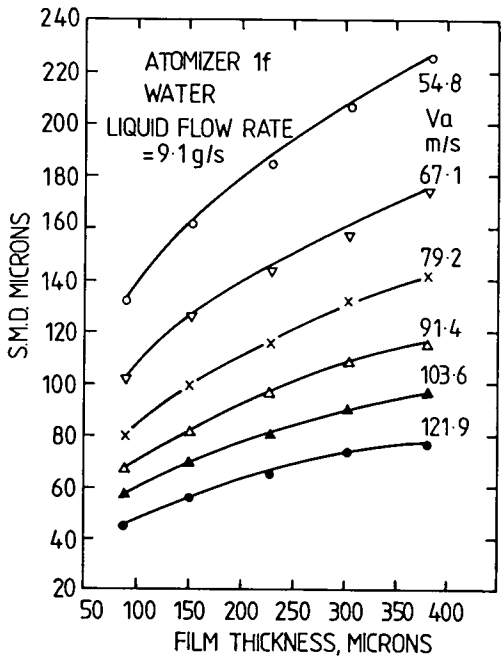


FIG. 7. EFFECT OF FILM THICKNESS ON SMD FOR VARIOUS AIR VELOCITIES¹⁰

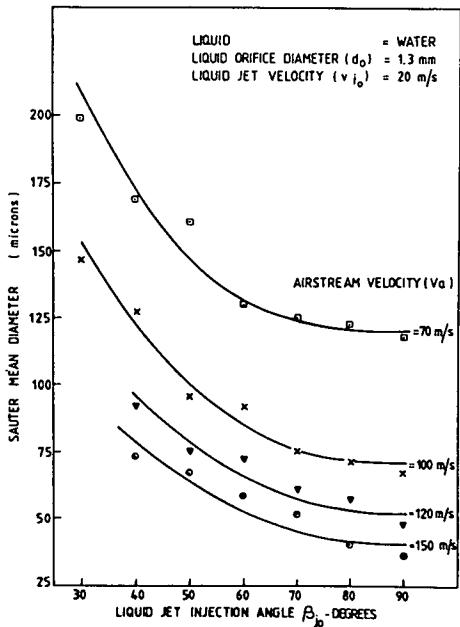


FIG. 8 VARIATION OF SMD WITH THE ANGLE OF INJECTION FOR VARIOUS AIRSTREAM VELOCITY LEVELS.

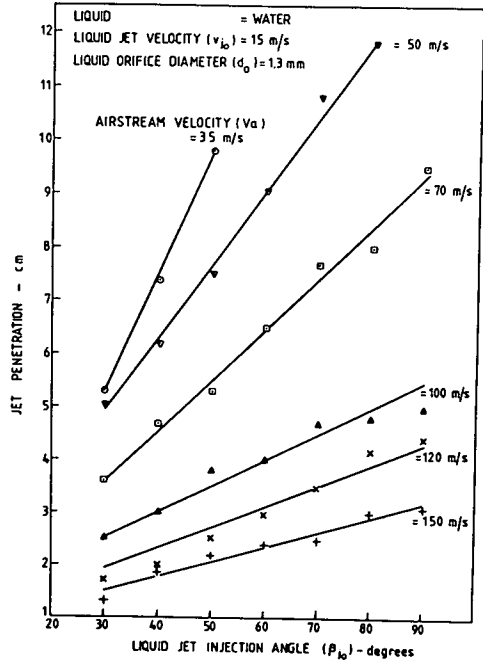


FIG. 9 VARIATION OF PENETRATION WITH THE LIQUID JET INJECTION ANGLE FOR DIFFERENT AIRSTREAM VELOCITIES.

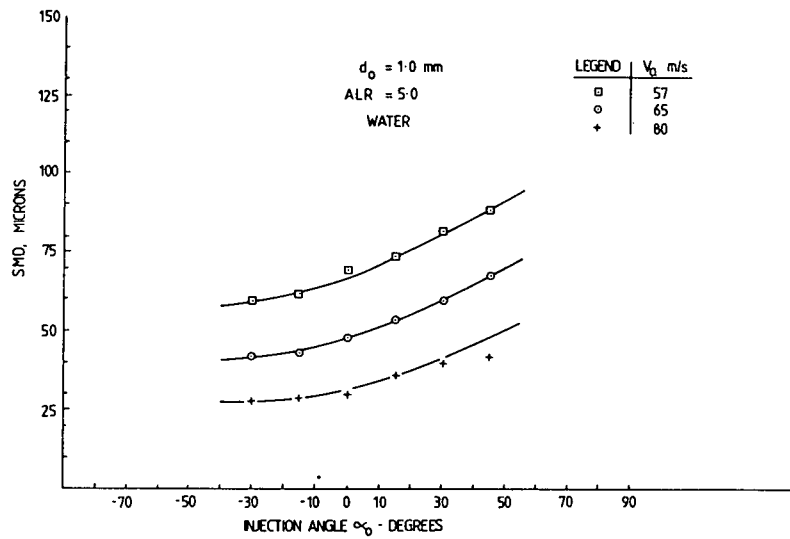


FIG. 10. VARIATION OF SMD WITH LONGITUDINAL INJECTION ANGLE (α_o)- $d_o = 1.00 \text{ mm}$

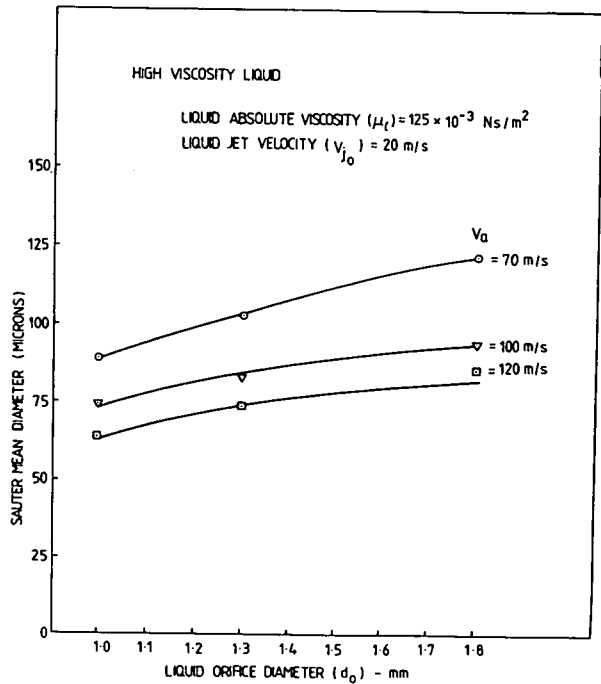


FIG. 11. LIQUID ORIFICE SCALE EFFECT FOR A HIGH-VISCOSITY LIQUID.

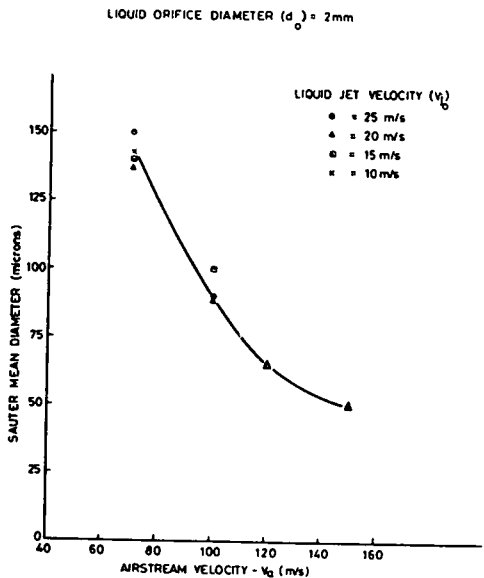


FIG. 12. EFFECT OF AIRSTREAM AND LIQUID JET VELOCITY UPON SPRAY MEAN DROPSIZE.

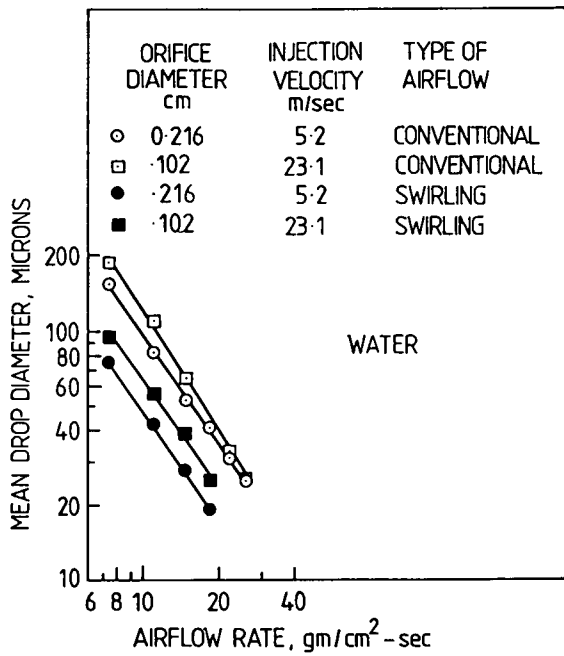


FIG. 13. VARIATION OF MEAN DROP DIAMETER WITH AIRSTREAM MOMENTUM FOR AXIAL DOWN-STREAM INJECTION WITH SINGLE TUBES¹³

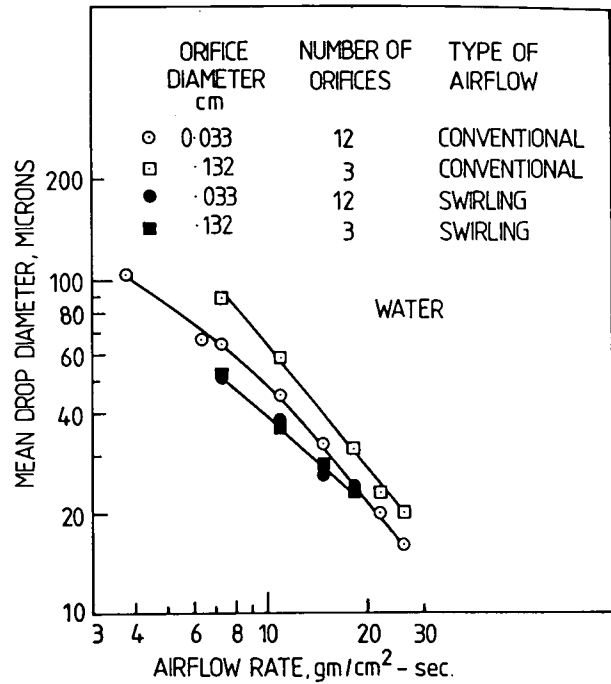


FIG. 14. VARIATION OF MEAN DROP DIAMETER WITH AIRSTREAM MOMENTUM FOR CROSS STREAM INJECTION WITH SPRAY BARS¹³

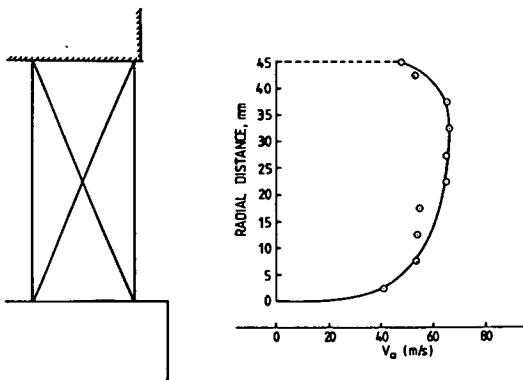


FIG. 15. DISTRIBUTION OF AIR AXIAL VELOCITY AT THE EXIT OF 45° CURVED-VANE SWIRLER

$\Delta P/P = 1.5$ PERCENT

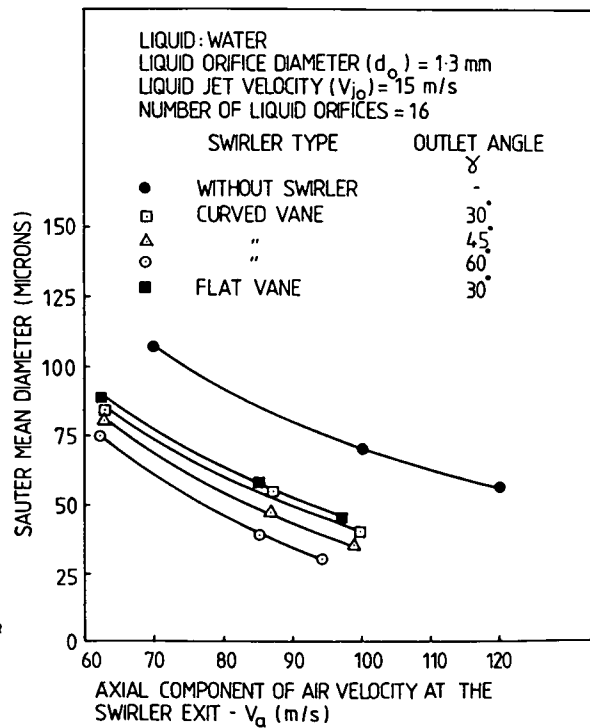


FIG. 16. VARIATION OF SPRAY SMD WITH AIRSTREAM VELOCITY FOR DIFFERENT SWIRLERS

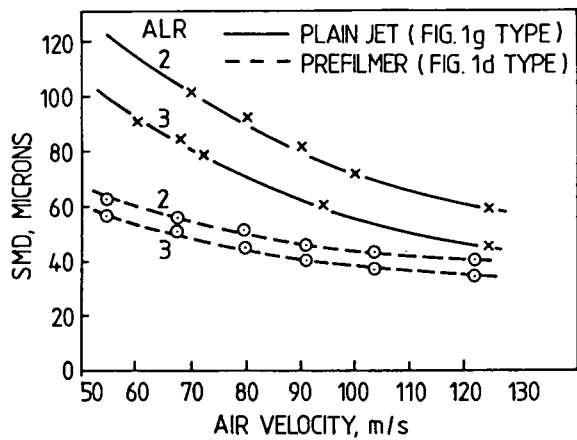


FIG. 17. COMPARISON OF ATOMIZING PERFORMANCE OF PLAIN-JET AND PREFILMING ATOMIZERS¹²

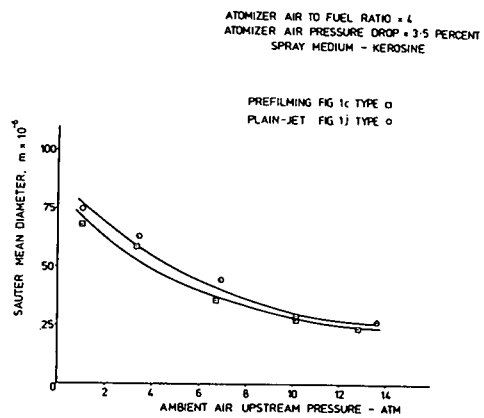


FIG. 18. COMPARATIVE PERFORMANCE OF PREFILMING AND PLAIN-JET AIRBLAST ATOMIZERS UNDER VARYING AMBIENT AIR UPSTREAM PRESSURES - KEROSENE

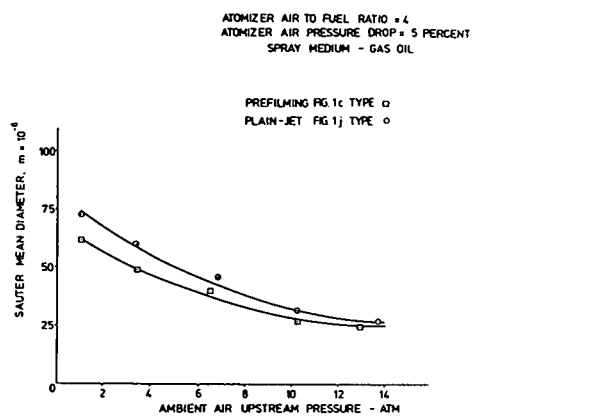


FIG. 19. COMPARATIVE PERFORMANCE OF PREFILMING AND PLAIN-JET AIRBLAST ATOMIZERS UNDER VARYING AMBIENT AIR UPSTREAM PRESSURES - GAS OIL

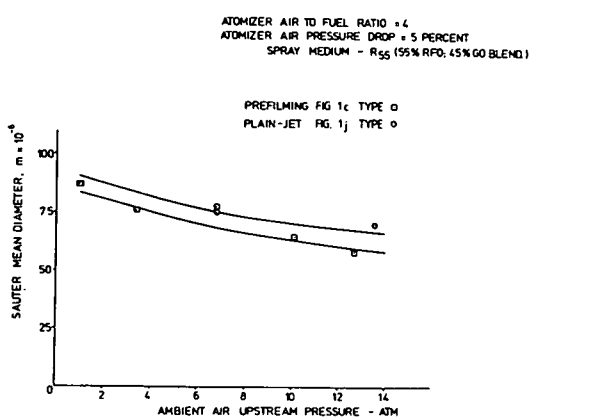


FIG. 20. COMPARATIVE PERFORMANCE OF PREFILMING AND PLAIN-JET AIRBLAST ATOMIZERS UNDER VARYING AMBIENT AIR UPSTREAM PRESSURES - R55 FUEL

DISCUSSION

E.Mularz, US

With respect to Figure 15, indeed the air flow through the swirler is important in determining the fuel spray quality of the fuel injector. However, your measurement of the axial component of air velocity is not sufficient, since there is a substantial component of circumferential velocity as well. I recommend that further measurements be made, more completely mapping this airflow through the swirler.

Author's Reply

The author agrees with Dr Mularz as regards the importance of more detailed mapping of the velocity flow-field at the exit of the air swirler. Indeed the first conclusion emphasizes the need for further work on the air swirler. Figures 15 and 16 were included in the paper to highlight, from the atomization performance viewpoint, the importance of air swirler vane geometry as well as the detailed understanding of the swirler velocity flow-field as typified by the axial velocity measurements. It was neither implied nor suggested that the axial velocity component was the only one that mattered. Indeed there is a substantial swirl component, the value of which depends upon the vane outlet angle. For example, the swirl component is approximately 80 percent of the axial component for the 45° curved vane swirler case of Figure 15. Figure 16 could be replotted using the swirl velocity component as the basis, but the basic conclusions would remain unchanged.

Effect of Air Pressure Upon Spray Angle/Width Characteristics of Simplex Pressure Swirl Atomizers

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Abstract

This paper examines the spatial distribution characteristics of fuel sprays emanating from simplex pressure swirl atomizers of the type commonly used in the gas turbine engine. Three different atomizers were tested on kerosine at chamber gas pressures up to 1377 KN/m^2 and fuel pressure drops up to 3448 KN/m^2 . A non-intrusive, still photographic technique was developed for recording the spray profiles over the entire range of test conditions. Analysis of the experimental data shows that the closing in of the spray boundaries due to an increase in air pressure is a result of the aerodynamic interaction between the fuel spray and its gaseous environment – the nozzle hydrodynamics apparently exercising no influence. Experimental data collected in the study reveals the influence of gas pressure (P_a) upon the half width (y) of the spray envelope at a downstream distance of 30 mm from the nozzle face to be described adequately by the expression $y \propto P_a^{-0.26}$.

Nomenclature

NN	Nozzle number, US Gallon/hr
FN ₁	Flow number, (Imperial Gal/hr)/(psi) ^{0.5}
FN ₂	Flow number, (m ³ /s)/(N/m ²) ^{0.5}
P	Pressure, KN/m ²
ΔP	Pressure drop, KN/m ² or psi
R	Correlation coefficient
y	Spray half width
n ₁ , n ₂	Exponents for variables P_a and ΔP_f
2θ	Spray cone angle

Subscripts

a	air or gas
f	fuel

Introduction

The characteristics of the spray emanating from a fuel injector are well-known to influence strongly the combustion-emissions performance of the gas turbine engine. For this reason numerous investigations have been conducted in order to extend the state of knowledge regarding the detailed structure of the fuel spray. The attention so far has, in the main, been focussed upon the quality of atomization as indicated by the sizes of the drops produced as a result of the disintegration process, and its relationship to the injector design/operating conditions as well as the fuel properties.

The purpose of this paper is to examine in some detail the spatial distribution characteristics of the fuel spray emerging from a simplex type of

pressure swirl atomizer. Despite the fact that such atomizers have been used extensively in the gas turbine industry, little is known about this particular aspect of its operation especially under conditions of varying air density. A knowledge of the spray boundaries/trajectories over the entire range of combustor operating conditions is essential to allow excessive variations in fuel-air mixture concentration within the burning zone to be avoided. Non-uniform and variable nature of spatial distribution of fuel spray is clearly a source of increasing concern due to its adverse impact upon the combustion-emissions performance of the gas turbine engine. It may be argued that the vastly superior performance of the airblast and vaporizing type of fuel injection systems obviates the need for further serious study of the pressure atomizer. However, very considerable interest still remains in them due to the large number of such atomizers that are still in service today. As a matter of fact, the interest in the simplex pressure atomizer is enhanced further due to the fact that it provides a pilot/starting jet with wide stability limits and is consequently common to the dual-orifice pressure atomizer, the hybrid airblast atomizer and the vaporizing type of fuel injection system.

A review of the previously published work in the open literature identified the work of DeCorso and Kemeny /1/, Neya and Sato /2/, Clare /3/ and Dodge and Biaglow /4/ as being relevant to the present study. In general, the range of air pressures covered in the earlier work has tended to be modest – a maximum of up to about 800 KN/m² for references /1/ to /3/, and up to about 1300 KN/m² for reference /4/. Furthermore, the spray boundary/angle data presented thus far has been for a single location within the spray envelope. This location has tended to be either too near (10 mm in ref. /4/) or too far (115 and 200 mm in refs. /1/ and /2/ respectively) from the atomizer face, in relation to the length of the gas turbine combustor primary zone. This study was aimed at remedying some of these shortcomings and consequently providing a better insight into the structure of the fuel spray. Further details regarding the study can be found in ref. /5/.

Experimental Details

Three commercially available simplex pressure swirl atomizers designed to generate a conical spray

that is hollow in character were selected for this investigation. The nozzle characteristics are detailed below:

Make	NN	2θ	FN ₁	FN ₂
Delavan	6.0	70°	0.5	0.76×10^{-8}
Delavan	1.5	90°	0.125	0.19×10^{-8}
Danfoss	6.3	80°	0.525	0.798×10^{-8}

The nozzle number (NN) in the table above indicates the rated volumetric flow of No. 2 oil in US gallons per hour at a pressure difference of 100 psi (689 KN/m²) while θ indicates the rated spray cone half angle. It was hoped that the results obtained would allow an insight into the effect of such variables as different manufacturing practices as well as different flow ratings in addition to those due to operational variables of air density and fuel pressure.

The experimental set up used in this study is illustrated in Fig. 1. Optical windows were incorporated into the pressure chamber for monitoring the atomized spray envelope under conditions of varying air density. Air at pressure up to about 1400 KN/m² was obtained from the main laboratory system and was introduced into the pressure vessel at a point somewhat removed from the injector but close to the optical windows. Some of the tests featured the use of high pressure bottled nitrogen gas. Stagnant gas (i.e. no through flow) conditions were maintained in the pressure vessel due to considerations of cost and complexity. The effect of various air flows within the combustor

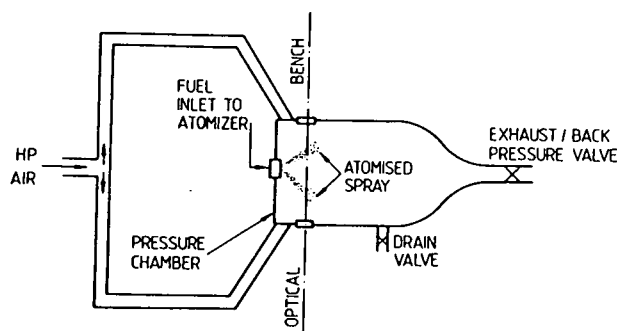


Fig. 1. Outline arrangement of the test installation.

primary zone has, in other words, not been examined here. The temperature of the gas throughout the test series was close to ambient. Standard kerosine, at ambient temperature, was used exclusively during the study. The fuel pressure drop across the injector was monitored through the use of calibrated pressure gauge connected close to the injector inlet.

The atomized spray profiles were determined through the use of still photography using side illuminations (i.e. at 90° to camera axis). This technique has the advantage of being simple, fast and non-intrusive relative to those adopted in refs. /1/ and /2/. De Corso and Kemeny /1/ used an intrusive, non-isokinetic spray sampling system comprising of 28 radial patternator tubes to obtain mass weighted spray distribution information along an arc of 115 mm radius. Neya and Sato /2/, however, used the immersion method to obtain spray samples at several points along an arc of 200 mm radius. The mass weighted patternation information was in both cases mathematically reduced to yield an equivalent spray angle. The results thus obtained were valid only for the single sampling location within the spray envelope. By contrast the photographic approach adopted here allowed a far greater proportion of the spray envelope to be studied — in fact the microfiche viewer analysis (see Analysis of Photographic Data section) allowed the first 45 mm of the spray length to be examined for any number of locations. Furthermore, the work of Tishkoff *et al.* /6/ reveals the presence of only minor differences when observing the spray plume boundaries through the use of conventional photography, pulsed laser shadowgraphy and in-line infra red spectroscopy. Jones /7/ discussed briefly the effect of the light source location on the measured spray angle and suggests a possible error of only a few degrees due to the use of side illumination.

Results and Discussion

Plate 1 illustrates the structure of the kerosine spray emerging from the simplex pressure swirl atomizer for fuel pressure drop in the 689.5 to 3447.5 KN/m^2 (100 to 500 psi) and chamber gas pressure in the 101.3 to 1376.6 KN/m^2 (1 to 14 atmosphere) range. As can be seen the photographs are by and large of good quality as little or no fuel

mist is present. This was important because the presence of large quantities of fine mist would obscure the spray making the boundary less distinct and the subsequent analysis harder as well as less accurate. This was accomplished by fuelling the injector for the minimum amount of time necessary for obtaining a representative photograph. In between test points, the fuel supply to the injector was shut off and the chamber purged briefly. Continuous fuel supply to the injector was, after some time, found to bring the chamber gas into motion due to the transfer of momentum from the swirling fuel droplets. The swirling type of motion generated in the chamber was sufficient to influence the spray structure, especially at high air density.

The character of the fuel spray can be clearly observed in Plate 1 to be strongly influenced by the ambient gas pressure — the spray width contraction being largest at the lowest fuel pressure drop of 689.5 KN/m^2 . Furthermore, the boundaries of the spray change from near-straight to increasingly curvilinear in character as the chamber gas pressure is increased. Both these observations are in agreement with those reported in Ref. 8. The effect of varying the fuel pressure drop at a constant level of chamber gas pressure can be seen to be largely confined to the 101.3 and 307.8 KN/m^2 gas pressure conditions. At higher gas pressures the effect is not significant. Due to limitations of cost and space experimental photographic data presented in this paper is being restricted to Plate 1. Further data is contained in ref. /5/.

Analysis of Photographic Data

The photographs provide a qualitative assessment of the effects that different variables have upon the spray plume boundaries but the usefulness/applicability of such trends is rather limited unless a mathematical/empirical correlating expression can be developed. Large amount of photographic data collected in this study allows such an attempt to be made in contrast to the limited amount of data collected on the behaviour of the pilot nozzle in ref. /8/. It was felt that if the spray profiles could be described by polynomial expressions which could be stored in a computer, then any required aspect of the curve geometry could be examined readily.

With the above objective in mind, a standard routine was established. The negatives were pro-

NOZZLE: - DELAVAN 6.0 70°

Chamber
Pressure
KN/m²abs

Nozzle Pressure Drop

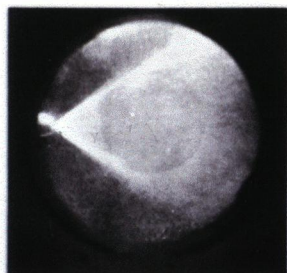
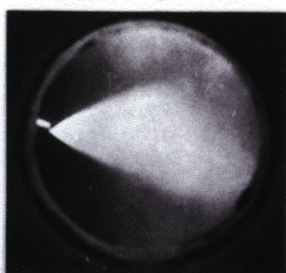
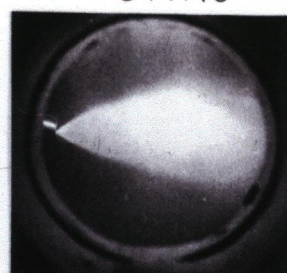
KN/m²

689.5

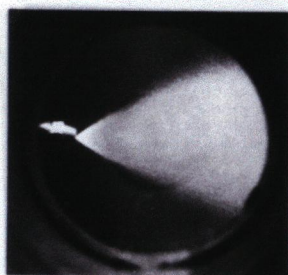
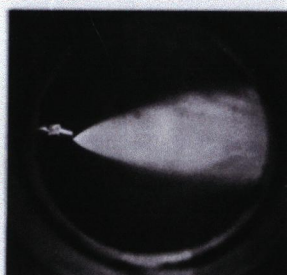
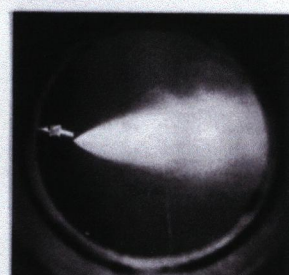
2068.5

3447.5

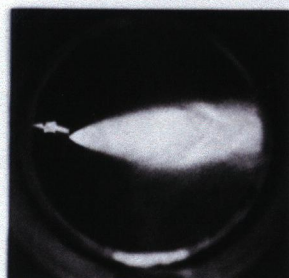
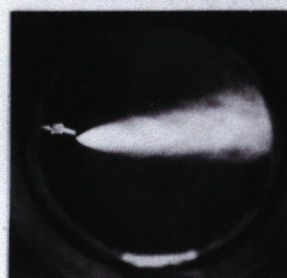
101.3



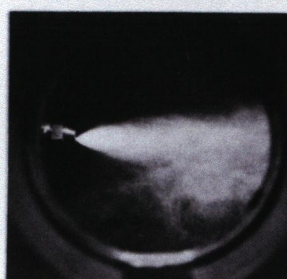
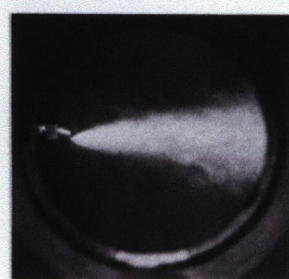
342.3



721.5



928.4



1376.6



jected onto the screen of a microfiche reader and the outer most visible boundaries of the spray plume copied onto a sheet of tracing paper. The axis of symmetry of this tracing was identified, using a sheet of graph paper, and the origin of a system of x-y co-ordinates was placed at the discharge orifice. The distance from the x-axis to the spray boundary (i.e. y-ordinate) was measured for both sides at steps of $x = 10$ mm for a total of 15 intervals. The two values of y for a given value of x were averaged and fed into the computer in order to fit them to a fourth order polynomial expansion by the least squares method. The resulting coefficients were stored in the computer along with the test details for further analysis.

It should be pointed out here that the microfiche reader was checked for and found to be free from distortion. Furthermore, it was found to afford analysis of the spray up to a maximum axial distance of 45 mm (from the injector face) on the real life scale. This was considered to be adequate for the purposes of developing an insight into the nature of changes that the structure of the spray undergoes within the confines of a typical combustor primary zone length. The use of the microfiche viewer was observed to give a magnification of 3.33 and to bring the analysis back to life size a multiplication factor of 0.3 was incorporated into the computer calculations.

Spray Angle Results

A review of the open literature reveals two commonly used definitions for the term spray angle. Giffen and Murasjew [9] defined the spray cone angle as the angle between the tangents to the spray envelope at the atomizer orifice. DeCorso and Kemeny as well as Neya and Sato adopted this definition for their research reported in refs. [1] and [2] respectively. Others including Lefebvre [10], Clare, Gardiner and Neale [11] and more recently Dodge and Biaglow [4] have preferred to define the spray cone angle as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the atomizer face. In other words it is the angle related to the spray width at a specified axial distance from the discharge orifice. There is a drawback to this latter definition because the shape of the spray contours is complicated and there

can be large number of spray profiles sharing the same angle simply by sharing the same width at the specified location. On either side of this location, however, the spray widths may be significantly different. For this reason, it must be borne in mind that this definition is, strictly speaking, applicable at the specified location only and may result in erroneous conclusions if considered to be more generally applicable.

Figure 2 shows the effect of chamber gas pressure for two different fuel pressure drops on the spray angle at the discharge orifice (consistent with Giffen and Murasjew's definition) for the Delavan 6 GPH/70° rated injector. The spray angle values were obtained by taking tangents to the polynomial at $x = 0$. Despite the fact that the results seem to exhibit some scatter, the authors believe that they are generally more consistent and accurate than would have been obtained if visual assessment had been adopted for drawing tangent to the various curves. Figure 3 shows the effect of fuel pressure drop on the spray angle for the same nozzle at a chamber gas pressure of about 618 KN/m^2 . It is clear from these figures that the spray angle at discharge orifice is practically insensitive to variations in fuel and ambient gas pressures. This would seem to imply that the nozzle hydrodynamics has little, if any, relationship with gas/fuel pressure variables – being largely determined by the initial design.

Spray Width Results

A knowledge of the spray angle at the discharge orifice is of limited interest to the engineer who

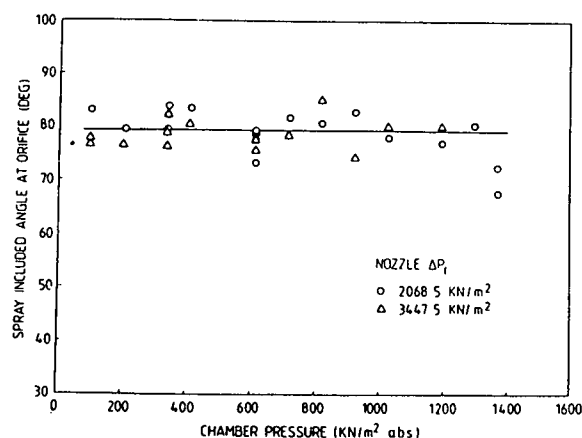


Fig. 2. Effect of air pressure on spray angle – Delavan 6.0/70° Nozzle

is faced with the task of achieving satisfactory combustion-emissions performance by avoiding excessive variations in fuel-air mixture concentration within the burning zone. Knowledge of the spray plume width as well as an understanding of the effect of key variables on it within the confines of the primary zone is clearly necessary if fuel and air are to be effectively mixed. As indicated before, the spray width analysis could be conducted for any number of axial locations upto a maximum distance of 45 mm from the nozzle face. For the sake of brevity and relevance to combustor primary zone, it was decided to restrict the analysis in the first instance to a single location – that corresponding to a distance of 30 mm from the nozzle face. This analysis can, in future, be extended to cover other locations if considered appropriate.

Figure 4 shows the effect of chamber gas pressure upon the spray envelope width for the Delavan 6GPH/70° injector at two different levels of fuel pressure drop. An increase in gas density can clearly be observed to result in a significant reduction in the spray plume width. The spray contraction curves seem to suggest a high rate of contraction at low levels of chamber pressure in marked contrast to the levelling off at chamber gas pressures of about 10^3 KN/m² and above. It has been established before that the increase in chamber gas pressure does not alter the liquid trajectory/angle at the point of discharge despite the inevitable increase in the pressure of the gas core (and hence the frictional drag due to it) within the swirl chamber. In other words the axial/tangential velocity characteristics of the liquid at the discharge orifice exit are unaffected by the changes in ambient gas pressure. Consequently, the reduction in the spray plume width is due to the aerodynamic interaction of the fuel spray with the gaseous environment into which it is injected. The results collected herein, however, do not extend the current state of knowledge regarding the precise mechanism that is responsible for spray contraction/boundary curvature.

The effect of nozzle fuel pressure drop on spray width at chamber gas pressures of 101 and 1377 KN/m² is illustrated in Figure 5. The influence exerted by nozzle pressure drop can clearly be seen to diminish with increasing ambient gas pressures. As a matter of fact for gas pressures of about 1000 KN/m² and above, the effect is barely noticeable. It is quite obvious that the fuel pressure

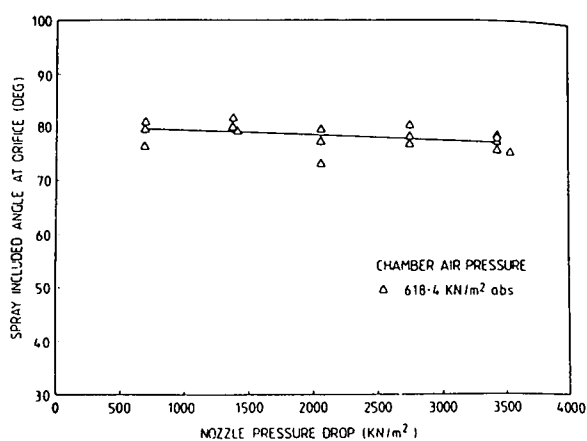


Fig. 3. Effect of fuel pressure drop on spray angle – Delavan 6.0/70° Nozzle.

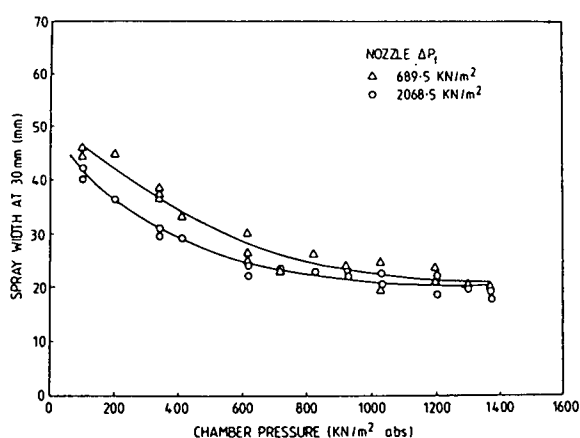


Fig. 4. Variation of spray envelope width with chamber air pressure – Delavan 6.0/70° Nozzle.

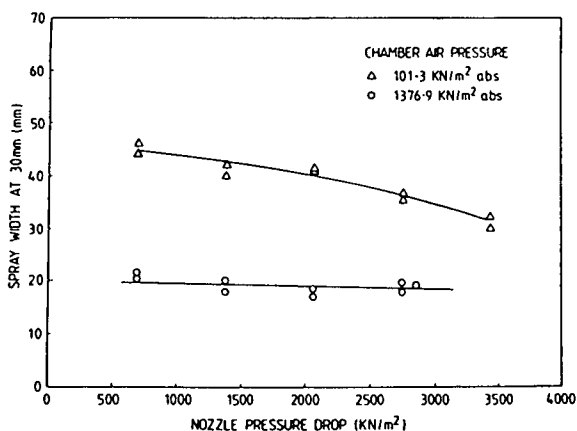


Fig. 5. Variation of spray plume width with fuel pressure drop – Delavan 6.0/70° Nozzle.

drop is playing a role that is secondary to that of the gas pressure.

The extent to which the spray results are specific to nozzles of a given make, i.e. those featuring common manufacturing practice, is a question that arises frequently. In other words the influence that the manufacturing practice exerts upon the spray performance needs to be identified if misleading generalisations are to be avoided. Figures 6 and 7 show some comparative results on Delavan 6GPH/70° and Danfoss 6.3GPH/80° nominally rated nozzles in an attempt to resolve the issue. The two injectors behave in much the same manner as the chamber gas pressure and fuel pressure drops are varied thus implying that the spatial distribution characteristics of pressure atomized simplex sprays are not significantly influenced by variations in manufacturing practice/internal geometry. This reinforces the view that the reduction in the spray plume width is a result of the aerodynamic interaction of the fuel spray with its gaseous environment after emerging from the discharge orifice. Incidentally, the nozzle with the larger nominal spray angle can be seen to yield a consistently wider spray plume. This is only to be expected from two nozzles that are of nearly identical flow number.

The effect of nozzle flow number on the spray envelope width for Delavan 1.5GPH/90° and Danfoss 6.3GPH/80° nozzles, bearing in mind the earlier observation that the impact of the different manufacturing practices is unlikely to be serious, can be seen in Figures 8 and 9. For a fuel pressure drop of 689.5 KN/m² the Delavan spray plume is wider due to its greater nominal cone angle but can be seen to reduce at a faster rate with increases in chamber gas pressure. This is in marked contrast with the curves shown on Figure 9 for a fuel pressure drop of 3447.5 KN/m² – not only are the two curves of a generally similar character but also the spray width of the Delavan injector with its nominally larger cone angle is less than that for the Danfoss injector. It should be pointed out here that the smaller flow number nozzle generates a finer spray for a given fuel pressure drop and consequently its data are prone to more scatter due to the possible obscuration of the spray boundary through mist build up. None the less the results indicate that the effect of nozzle flow number upon spray width is dependent upon the fuel pressure drop through possibly its effect upon the droplet

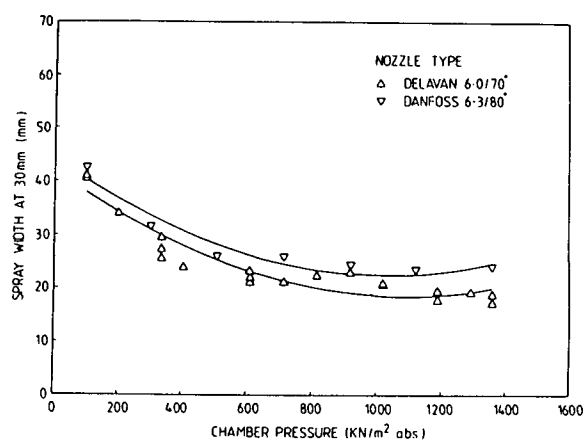


Fig. 6. Effect of nozzle make on spray envelope width – $\Delta P_f = 2068.5 \text{ KN/m}^2$.

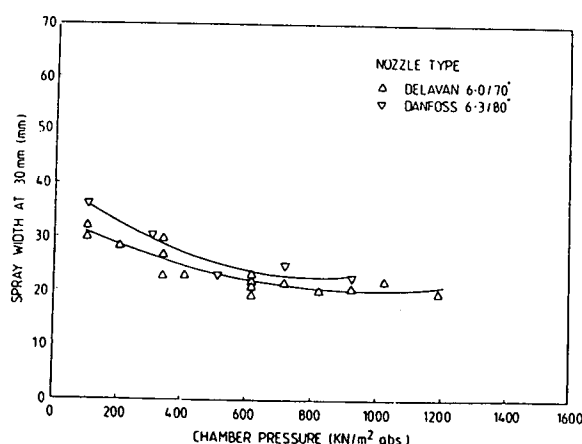


Fig. 7. Effect of nozzle make on spray plume width – $\Delta P_f = 3447.5 \text{ KN/m}^2$.

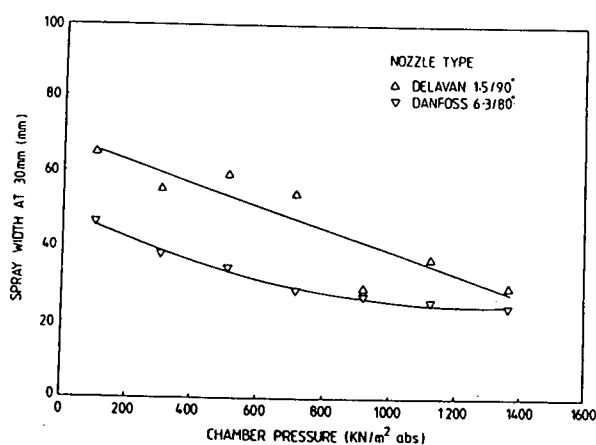


Fig. 8. Effect of nozzle flow number on spray width – $\Delta P_f = 689.5 \text{ KN/m}^2$.

momentum/drag ratio. This is clearly an avenue for further research partly due to the uncertainty regarding the extent to which the droplets have been generated by the 30 mm station and partly due to the rather small flow number nozzle operating at a high fuel pressure drop.

Correlation of Results

The foregoing spray plume width data, relating to the 30 mm station, was subjected to systematic evaluation using the conventional log-log analysis methodology in an attempt to correlate it with gas pressure (P_a) and fuel pressure drop (ΔP_f) – see Figures 10, 11 and 12 for example. The method of least squares was used to fit the straight line to the experimental data and the following gradient/exponent and the correlation coefficients (R) were obtained:

	Delavan 6GPH/70°	Danfoss 6.3GPH/80°	Range
P_a	-0.276	-0.241	$689 \leq \Delta P_f \leq 3450 \text{ KN/m}^2$
R	0.90 to 0.97	0.95 to 0.98	
ΔP_f	-0.184	-0.166	$100 \leq P_a \leq 600 \text{ KN/m}^2$
R	0.7 to 0.88	0.92 to 0.96	

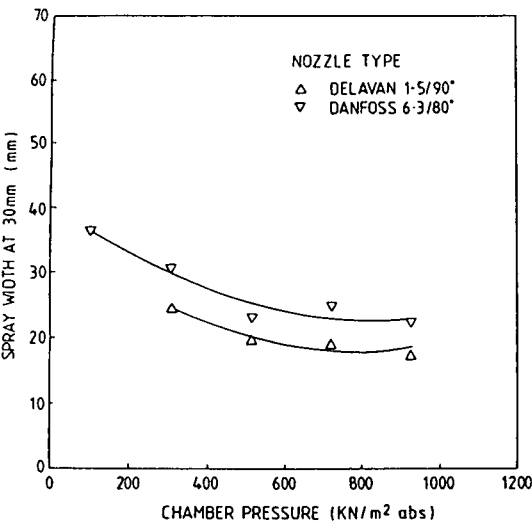


Fig. 9. Effect of nozzle flow number on spray width – $\Delta P_f = 3447.5 \text{ KN/m}^2$.

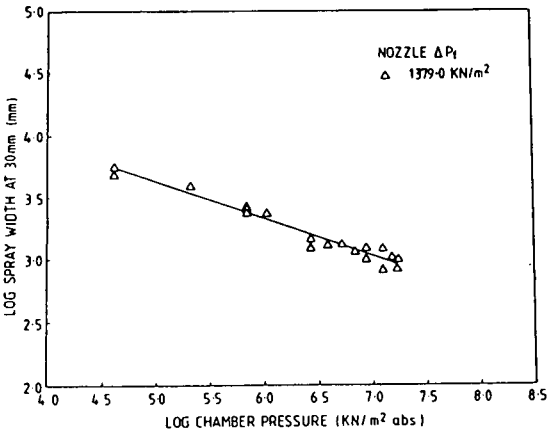


Fig. 10. Correlation of spray width with chamber air pressure – Delavan 6.0/70° Nozzle.

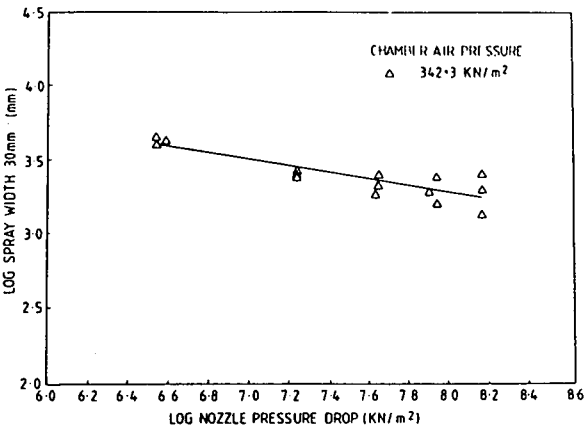


Fig. 11. Correlation of spray width with nozzle pressure drop – Delavan 6.0/70° Nozzle.

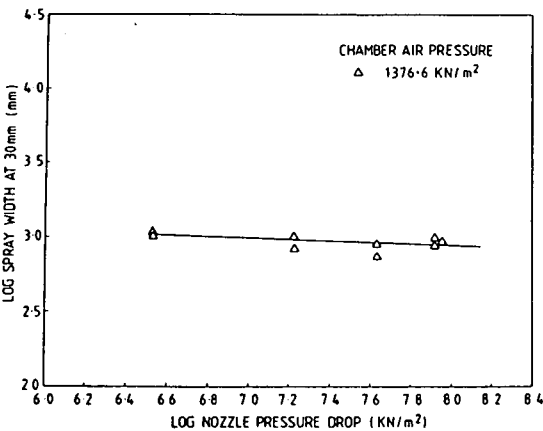


Fig. 12. Correlation of spray width with nozzle pressure drop – Delavan 6.0/70° Nozzle.

In other words P_a and ΔP_f influence the spray half width 'y' in accordance with the expressions $y \propto P_a^{n_1}$ and $y \propto \Delta P_f^{n_2}$ where the average value of $n_1 = -0.26$ for ΔP_f in the 689 to 3450 KN/m² range and that of $n_2 = -0.175$ for P_a up to about 600 KN/m². The value of n_2 for gas pressures above about 700 KN/m² is negligibly small. The 1.5 GPH/90° Delavan injector gave a value of $n_2 = -0.61$ and consequently would seem worthy of further study due to its markedly different behaviour relative to the other two injectors. It is not clear whether the operation of a small flow number nozzle at a high fuel pressure drop encourages the hydrodynamic behaviour of the nozzle to change which in turn will influence the characteristics of the liquid at the point of discharge.

Comparison of the findings of this investigation with those reported by previous researchers, notably DeCorso – Kemeny /1/ and Neya – Sato /2/ is hindered by many factors. The measurement technique as well as the experimental set up employed in the earlier studies is significantly different from that adopted in this study. Both the previous studies used intrusive, non iso-kinetic collection/sampling tube set ups for ascertaining the effect of air and fuel pressures on the mass distribution of liquid within the spray envelope in contrast to the non-intrusive, photographic approach adopted in the present work. DeCorso and Kemeny's spray contraction data was obtained at a sampling station located 114 mm from the nozzle tip and that of Neya and Sato's at 200 mm while that presented in this paper has been obtained at a distance of 30 mm – more consistent with the primary zone lengths of the current combustors. Another aspect that is worthy of mention here is the fact that in both the previous studies the injectors were located so as to discharge the fuel spray in a vertical direction in contrast to the horizontally discharged spray set up of this study. This may have some implications as regards the gravitational effect on the spray droplet trajectory in a high gas pressure environment.

Conclusions

The main conclusions that can be drawn from this work are as follows:

(1) Spray angle at the discharge orifice is insensitive to gas and fuel pressure variations.

(2) The closing in of the spray boundaries at the 30 mm station due to an increase in ambient gas pressure is a result of the aerodynamic interaction between the fuel spray and its gaseous environment – the nozzle hydrodynamics apparently exercising no influence.

(3) The spray half width 'y', gas pressure ' P_a ' and fuel pressure drop ' ΔP_f ' are correlated by the expressions:

$$y \propto P_a^{-0.26} \quad \text{for } 689 \leq \Delta P_f \leq 3450 \text{ KN/m}^2$$

$$y \propto \Delta P_f^{-0.175} \quad \text{for } 100 \leq P_a \leq 600 \text{ KN/m}^2$$

at 30 mm from the nozzle face for the 6GPH/70° and 6.3GPH/80° rated nozzles. The behaviour of the small capacity nozzle (i.e. 1.5GPH/90°) is significantly different from the other two to make it worthy of further study.

(4) The spray envelope widths appear to be unaffected by the nozzle make.

Acknowledgement

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Dual-Orifice Atomizer Performance under Varying Air Density Conditions

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Abstract

The spray quality and spatial distribution characteristics of a pressure atomizer of the dual-orifice type have been experimentally investigated using the well-established, non-intrusive techniques of laser droplet sizing and photography. Tests were conducted on kerosine and gas oil at air pressures up to about 8 atmospheres. The characteristics of spray quality and spatial distribution have been shown to undergo a noticeable change over a wide range of main fuel flows. An increase in the air density results in an improvement in the spray quality, but, is accompanied with a reduction in spray penetration. The dropsize correlation evolved earlier for the simplex pressure atomizer has been applied with success to the dual-orifice atomizer featured in this investigation.

Nomenclature

- FN = atomizer flow number, $W/\sqrt{\Delta P}$
 SMD = Sauter Mean Diameter, m
 W = mass flow rate, kg/s
 ΔP = atomizer pressure drop, N/m²
 ρ = density, kg/m³
 σ = surface tension, N/m
 ν = kinematic viscosity, m²/s
 η = absolute viscosity, Ns/m²

Subscripts

- f = fuel
 p = pilot
 m = main

Introduction

The performance of a gas turbine combustor is well known to be strongly related to the quality of fuel preparation. Detailed knowledge of the behaviour of the fuel injector would, consequently, help considerably any attempts at developing a satisfactory understanding as well as the capability

to accurately predict and achieve the performance of a given combustion system. For this reason fuel injectors of the type used in the current generation of gas turbine engines have been subjected to numerous investigations. The attention has hitherto been focused upon the quality of atomization as indicated by the sizes of the drops produced, as a result of the disintegration process, and its relationship to the injector design/operating conditions as well as the fuel properties. There is, however, increasing concern with regard to the non-uniform and variable nature of spatial distribution of the fuel spray emanating from a given injector over the entire operational range of the combustion system. Excessive variations of the fuel-air mixture concentrations within the burning zone will adversely affect the combustion-emissions performance of the gas turbine engine.

The purpose of this paper is to examine in some detail the spray quality and spatial distribution characteristics of a pressure swirl atomizer of the dual-orifice type under varying air density conditions. Despite the fact that such atomizers have been used in gas turbine engines for a long time, little is known about many key aspects of their

operation. For example, the interactions taking place between the pilot and main sprays, together with the effect that air and liquid properties have upon the spray structure and performance are two critical areas worthy of detailed investigation. Even the recent pressure atomizer study reported in /1/ does not cover the dual-orifice type of injector. Furthermore, it gives no consideration to the effect of ambient air pressure upon the spatial distribution characteristics of the pressure atomized spray.

It may be argued that in view of the vastly superior combustion-pollution performance of the air-blast and vaporizing type of fuel injection systems (see /2/ and /3/), pressure atomizers need no further serious investigations. However, considerable interest still remains in them due to the very large number of pressure atomizers that are still in service today. Furthermore, the interest in the simplex pressure atomizer is even greater due to the fact that it provides a pilot/starting jet with very wide stability limits and is consequently common to the dual-orifice pressure atomizer (duple), the hybrid airblast atomizer, and the vaporizing type of fuel injection system. Relaxation in the quality of the future fuels as a result of cost and availability considerations coupled with the need to comply with the legislation restricting the pollutant emission were the added considerations for conducting this programme of research under the sponsorship of the British Ministry of Defence. Emphasis in this programme was placed upon the experimental research in an attempt to obtain spray quality and spatial distribution data relevant to the operation of gas turbine combustors over a range of air pressures and fuel viscosities.

Experimental Details

A standard dual-orifice injector of the type fitted to many engines in the last two decades was selected for this investigation. The flow rating as well as the visual spray quality of the injector was checked and observed to be satisfactory before the commencement of the experimental programme. Independent fuel supply lines along with control valves and pressure gauges were provided for the two nozzles. This was to enable the interaction of the pilot and main sprays to be examined over a range of fuel flows that were wider than would have ordinarily been possible through the use of a conventional pressurising valve set up.

Effects of fuel quality upon spray performance were confined to kerosine ($\eta = 0.0013$, $\sigma = 0.027$, $\rho = 784$) and gas oil ($\eta = 0.0053$, $\sigma = 0.0299$, $\rho = 846$). Calibrated flow meters and pressure gauges were used to establish the correct fuel flow conditions for the dual-orifice injector.

The experimental set up used in this study is shown in Fig. 1. Optical windows were incorporated into the pressure chamber for monitoring the atomized spray envelope as well as drop size under conditions of varying air density. High pressure air was obtained from the main laboratory system and was introduced into the pressure vessel at a point somewhat removed from the injector but close to the optical windows. Stagnant air flow (i.e. no through flow) conditions were maintained in the pressure chamber due to considerations of cost and complexity. The effect of various air flows in the combustor primary zone has, in other words, not been examined here. Furthermore, the temperature of the air throughout the test series was close to ambient.

The spray structure was determined through the use of still photography whereas drop size measurements were made by utilising the well-established, non-intrusive laser light-scattering technique. The optical technique is based upon the principles of forward diffractive scattering of a parallel, monochromatic beam of light as it passes through the test spray and is an extension of that originally developed by Dobbins *et al.* /4/. Generally speaking, the technique has been observed to yield satisfactory mean drop size results down to about 20 microns for a wide variety of fuel injector types as well as their operating conditions including those featuring high ambient air pressures.

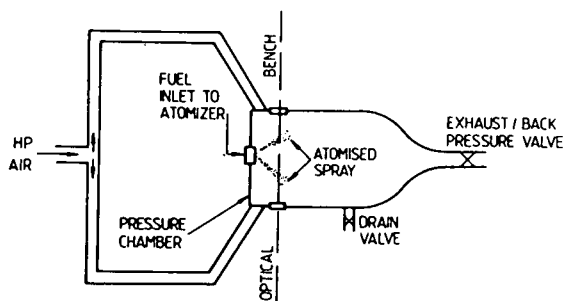


Fig. 1: Outline arrangement of the test installation

Results and Discussion

Photographic Investigation

The structure of kerosine spray emanating from the dual-orifice injector as a function of varying fuel flow is illustrated in Plate 1 for a chamber air pressure of 1 atmosphere. The variation in injector fuel flow was achieved by varying the quantity of fuel passing through the main nozzle whilst a constant pressure drop, relative to the chamber air pressure, of 300 psi was maintained across the pilot nozzle. This procedure was regarded as being typical of an engine's operational sequence. The precise effect that the initial opening of the pressurizing valve and therefore the admission of fuel through the main nozzle upon the spray quality and spatial distribution has been poorly documented in the open literature thus far. Little is known about the interactions taking place between the pilot and main sprays during this phase. An examination of Plate 1 reveals noticeable changes in the shape as well as the quality of the spray as the main fuel flow is progressively increased. The initiation of flow through the main nozzle is accompanied by very little pressure energy and consequently the fuel is being discharged not as a well-formed conical spray but as a dribble. This results in a noticeable degradation in the quality of the combined spray whilst the spatial distribution characteristics are not significantly modified initially. As the flow through the main nozzle increases, its pressure energy increases and this in turn yields a spray which is not only improving in quality but also features widening of boundaries progressively. Eventually the main spray assumes a well-formed conical structure; and, further increases in its flow rate (and hence pressure energy) result basically in an improvement in its quality alone. As a consequence the degradation in quality exhibited by the combined spray becomes less severe. Plate 1 confirms this and in addition shows the wide range of main fuel flow over which the characteristics of spray quality and spatial distribution are changing as the pilot and main sprays interact.

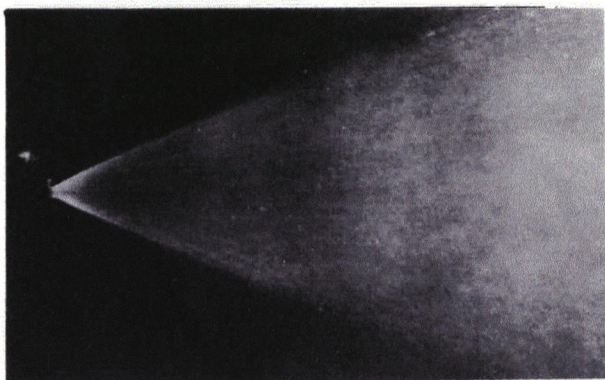
Plates 2 and 3 illustrate the structure of the dual-orifice injector spray at chamber air pressures of 5 and 8 atmospheres respectively. The shape of the pilot spray on its own, for a constant fuel pressure drop of 300 psi, can clearly be seen to

be strongly influenced by the ambient air pressure (Plate 2a and 3a against Plate 1a). The boundaries of the spray change in character from near-straight to increasingly curvilinear as the chamber air pressure is raised. A close examination reveals pronounced boundary changes in the structure of the far-field spray. On leaving the discharge orifice of the pilot nozzle the swirling sheet of liquid seems to follow much the same trajectory for the first few millimetres of its flight. This would seem to imply that the increase in the pressure of the air core inside the swirl chamber, an inevitable consequence of an increase in the chamber air pressure (see /5/), is not significantly altering the velocity characteristics of the liquid at the point of discharge. The subsequent movement of this sheet of liquid will, however, depend upon the characteristics of the prevailing environment. An increase in the chamber air pressure will result in the sheet/droplets encountering greater resistance and consequently their energy will be dissipated more rapidly to the surrounding gas. The effect of this increase in aerodynamic resistance in terms of reduced spray penetration will be expected to be more evident in the far-field.

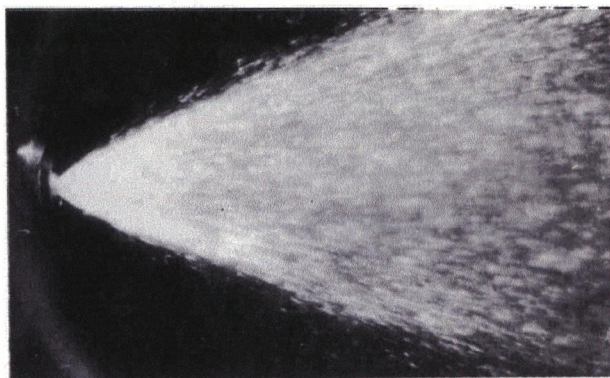
In addition to this, De Corso and Kemeny, /6/, suggest that a depression is created inside the hollow, air-cored spray due to gas entrainment and this generates a differential pressure across the liquid sheet. They argue that the magnitude of this pressure differential increases with an increase in chamber air pressure thus closing in the spray boundaries still further. The work of Neya and Sato, /7/, covering air pressure range of 3.56 to 71 psia, seems to be in agreement with their hypothesis. By cutting off the spray through the use of conduit pipes and hence improving the availability of air for entrainment around the inside of the spray, they claim to have restored the contraction of the spray boundaries over the range of air pressures investigated. The currently available evidence indicates that the change in the liquid trajectory accompanying the variation in the chamber air-pressure is due to the interaction of the hollow, air-cored spray with the environment that is external to the injector.

A progressive increase in the main fuel flow can be seen in Plates 2 and 3 to have a noticeable effect upon the shape as well as the quality of the spray even at higher (but fixed) chamber air pressures. Once again this changing state of spray spatial

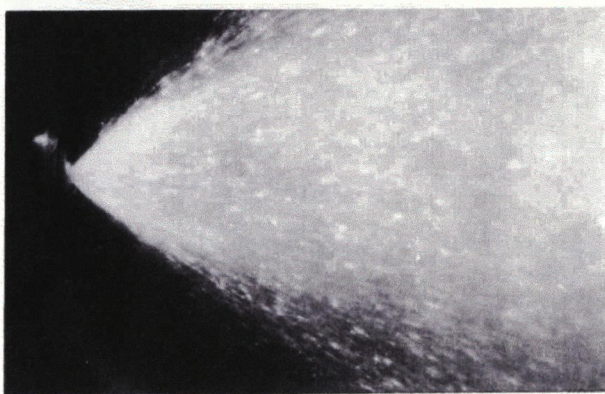
(a), Main flow - Nil



(b), Main flow = 13.5 GPH



(c), Main flow = 23.5 GPH

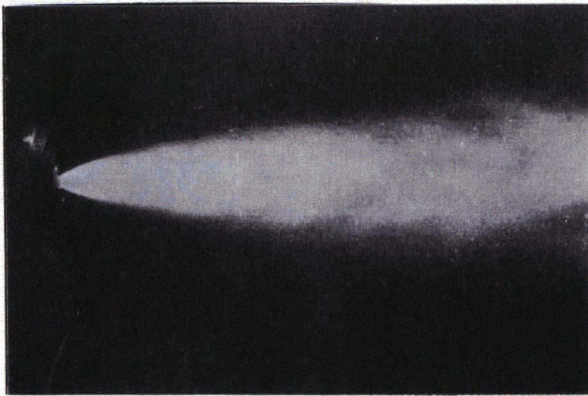


(d), Main flow = 45.2 GPH

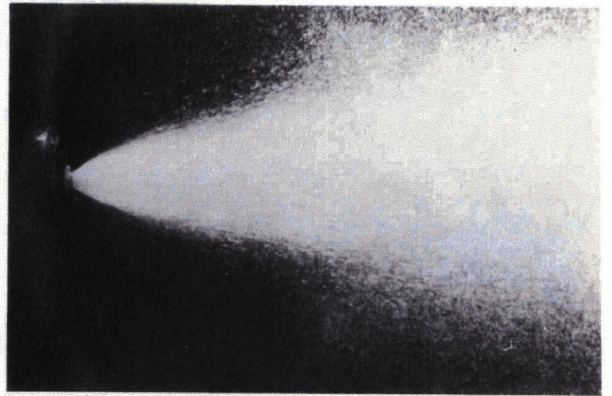


PILOT $\Delta P = 300$ psi (throughout)
PLATE 1 (1 ATMOSPHERE, KEROSENE)

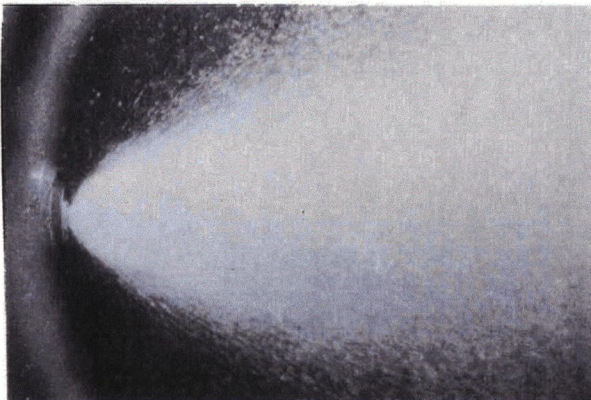
(a), Main flow = Nil



(b), Main flow = 11.3 GPH



(c), Main flow = 25.1 GPH



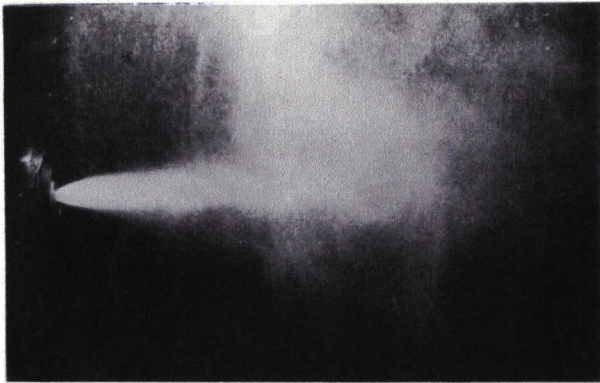
(d), Main flow = 58.8 GPH



PILOT ΔP = 300 psi (throughout)

PLATE 2 (5 ATMOSPHERE , KEROSENE)

(a), Main flow = Nil



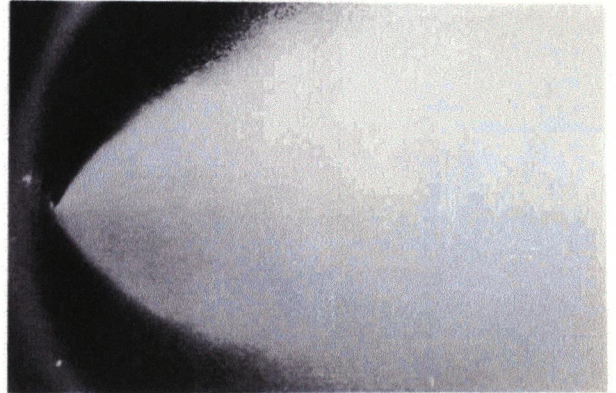
(b), Main flow = 22.2 GPH



(c), Main flow = 28.0 GPH



(d), Main flow = 46.5 GPH



PILOT $\Delta P = 300$ psi (throughout)
PLATE 3 (8 ATMOSPHERE, KEROSENE)

distribution and quality persists over a wide range of main fuel flows. Also evident is the increasingly curved nature of the combined pilot and main spray boundary as the chamber air pressure rises [e.g. Plate 3(d) against 1(d); 3(b) against 1(c)].

The dual-orifice injector operation at low chamber air pressures (up to 3 atmospheres) is shown in Plate 4. It is evident that even at such low chamber pressures the pilot spray boundaries are beginning to close in. Another interesting feature is the effect of fuel dribble from the main nozzle, as exemplified by Plate 4(d), on the atomization performance of the pilot. Clearly this is a situation where the fuel dribbling from the main nozzle is relying for its disintegration largely upon the energy of the pilot spray. This sharing of energy between the two sprays is usually achieved by careful attention to the cone angles of the pilot and main nozzles.

Due to the concern regarding the quality of future petroleum derived gas turbine fuels, it was considered prudent to conduct a limited investigation on gas oil. Plate 5 illustrates the effect upon spray performance of increasing the main fuel flow for a constant pressure drop of 300 psi across the pilot relative to a chamber air pressure of 3 atmospheres. It is interesting to note that even at a combined diesel flow of 40 gph the spray envelope is neither fully developed nor sufficiently well-atomized. The effect upon spray quality of diesel dribbling from the main nozzle as well as the performance of the dual-orifice injector at a high, combined diesel flow rate of 100 gph at various levels of chamber air pressures was also examined, /8/.

Dropsize Measurements

The photographic investigation was followed by a limited amount of spray mean drop size testing in an attempt to obtain a broad quantitative insight into the behaviour of the dual-orifice injector over a range of air and fuel variables. It is worth reiterating here that there is a distinct dearth regarding information of this kind – in the main drop size studies on simplex type of pressure swirl atomizers have been reported in the literature (see /1/, /7/, /9-11/). Figure 2 shows the effect upon atomization performance of varying the kerosine and diesel flow rates through the dual-orifice injector under atmospheric pressure conditions. It should be borne

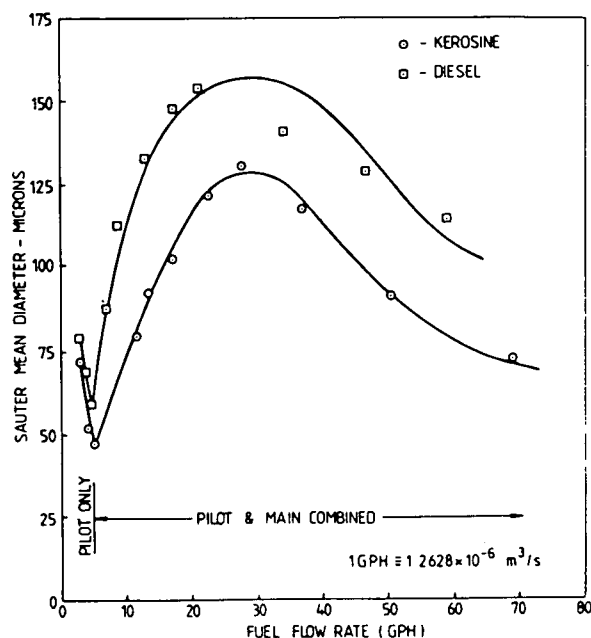


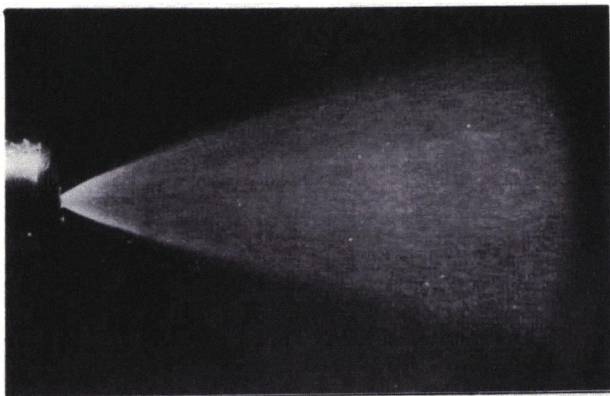
Fig. 2: Mean drop size performance under varying fuel flow conditions - 1 atm data

in mind that the combined mode of operation has been achieved here by maintaining a constant pressure drop of 300 psi across the pilot whilst varying the main flow – i.e. consistent with the approach adopted during the photographic investigation. Atomization quality can be seen to be somewhat poor over a wide range of fuel flows – starting from the point at which the fuel is initially discharged from the main nozzle in the form of a dribble to a combined flow of around 40 gph. A similar state of affairs can be observed to prevail at a chamber air pressure of 5 atmospheres (Figure 3).

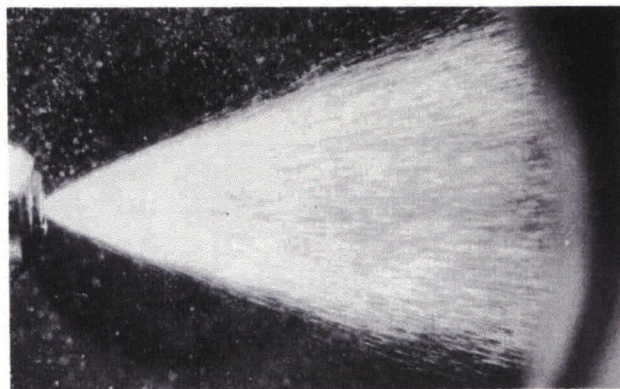
The effect of fuel quality upon spray mean drop size performance is also illustrated in Figures 2 and 3. The change from kerosine to gas oil (to BS Spec. 2869) as the spray medium has a degrading influence upon the spray behavior for 1 as well as 5 atmosphere chamber air pressure levels. The physical property of fuel that is principally responsible for this degradation is the absolute viscosity, because the change in both the density and the surface tension characteristics in going from kerosine to gas oil is insignificant relative to that for absolute viscosity.

An examination of the evidence currently available on the simplex type of pressure swirl atomizer

(a), $P_{\text{air}} = 2$ ats. (No main)



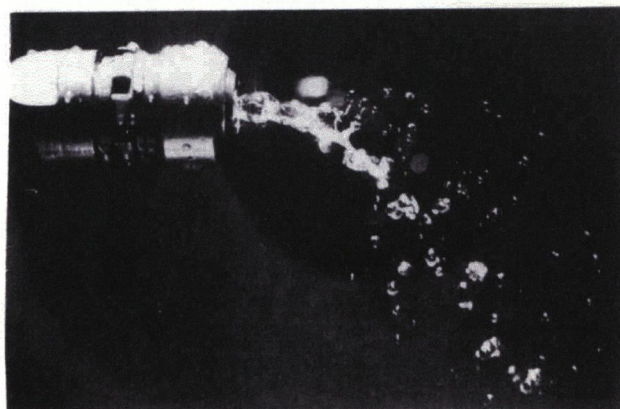
(b), $P_{\text{air}} = 1.5$ ats., Main dribbling



(c), $P_{\text{air}} = 3$ ats., Main dribbling

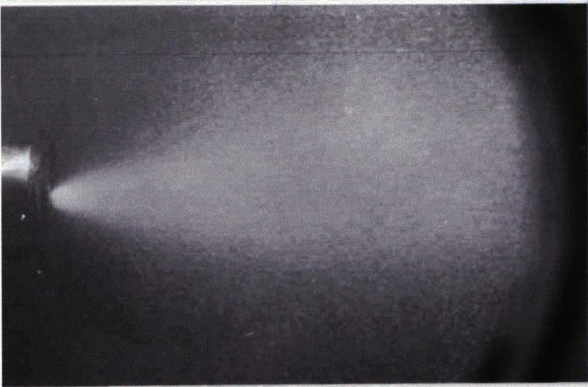


(d), Main dribble only

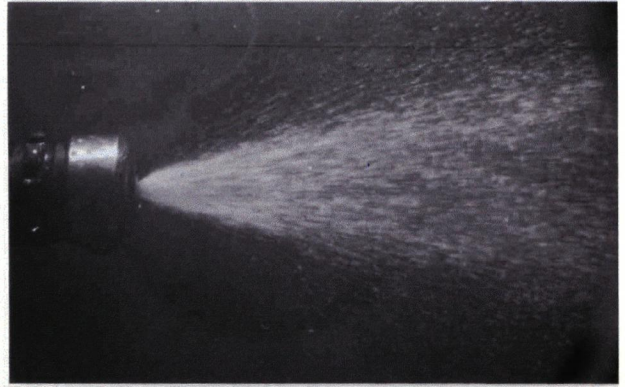


PILOT $\Delta P = 300$ psi (for a, b & c).
PLATE 4 (KEROSENE)

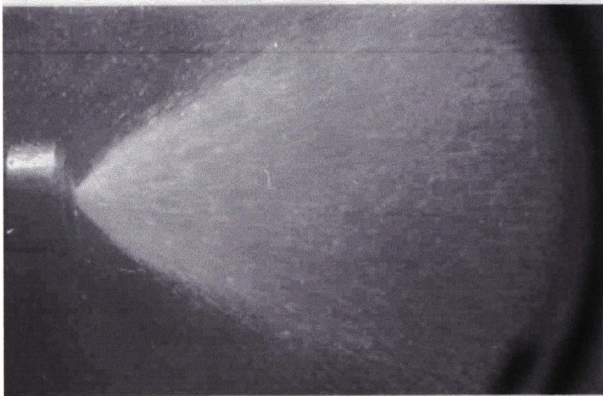
(a), Main dribbling



(b), Fuel flow = 20 GPH (Pilot + Main)



(c), Fuel flow = 40 GPH (Pilot + Main)



(d), Fuel flow = 80 GPH (Pilot + Main)

PILOT ΔP = 300 psi (throughout)

PLATE 5 (3 ATMOSPHERE, DIESEL)

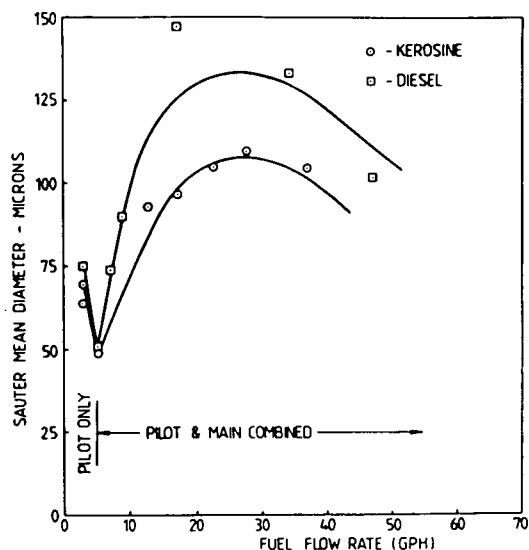


Fig. 3: Mean drop size performance under varying fuel flow conditions - SATM

reveals conflicting trends regarding the effect of ambient air pressure on spray quality. DeCorso, /9/, observed an increase in mean drop size with an increase in air pressure and this was confirmed by Neya and Sato, /7/. However, Giffen and Lamb /11/, Clare /10/, and Rizk and Lefebvre /1/, have all reported the opposite effect. The photographic results reported in the preceding section indicate a noticeable reduction in the spray width as the chamber air pressure increases. This closing in of the spray boundaries will, for a given quantity of liquid, be expected to result in an increase in the thickness of the liquid sheet undergoing break up. In addition, the droplets formed will have greater opportunities for coalescing with each other as the spray contracts. These adverse influences will, however, be opposed by an increase in the aerodynamic forces causing liquid break-up as the air density rises. The limited amount of data contained in Figures 2 and 3 has been cross-plotted in Figure 4 for gas oil and it does reveal a net reduction in the spray mean drops size as the air pressure is raised from 1 to 5 atmospheres. Clearly, this complex interaction warrants further research, especially over a range of air pressures that are more representative of the current gas turbine operation.

Correlation of Drops size Data

The spray quality characteristics of the dual-orifice atomizer studied here can be predicted by

utilising the drop size correlation developed for the simplex pressure atomizer when spraying in stagnant air at atmospheric pressure in an earlier study by the present author, /12/. The relevant correlation is given below:

$$SMD = 4.4 \nu_f^{0.16} \sigma_f^{0.6} W_f^{0.22} \Delta P_f^{-0.43} \quad (1)$$

Before the above correlation can be used for the dual-orifice atomizer, the terms W_f (fuel mass flow rate) and ΔP_f (fuel pressure drop) need clarification. W_f relates to the combined fuel flow rate whereas ΔP_f is the resultant fuel pressure drop for the combined spray. The combined fuel flow is readily ascertained, but there are two possibilities regarding the resultant fuel pressure drop – based upon the assumption that the pilot and main sprays coalesce with each other and share either their kinetic energy or momentum. Both the expressions are given below.

Momentum sharing:

$$W_f \sqrt{\Delta P_f} = W_{f,p} \sqrt{\Delta P_{f,p}} + W_{f,m} \sqrt{\Delta P_{f,m}}$$

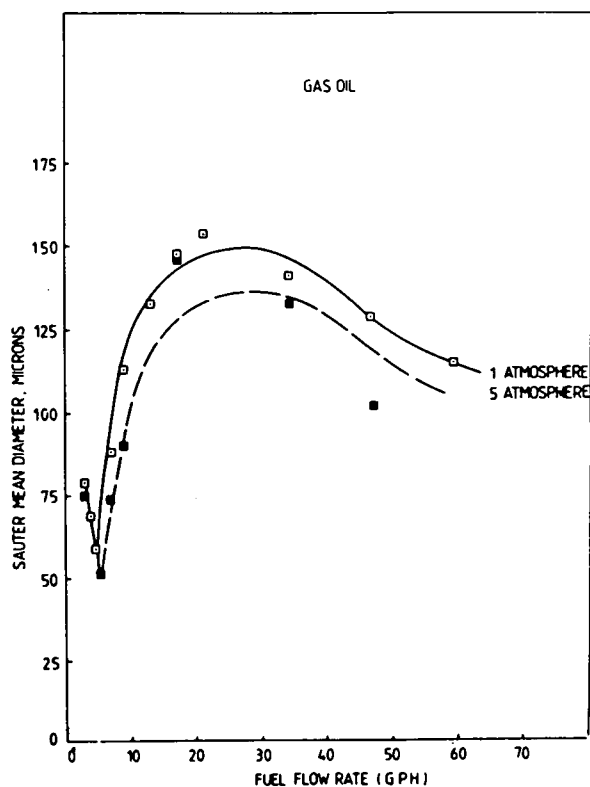


Fig. 4: Mean drops size performance under varying fuel flow and air pressure conditions

or

$$\Delta P_f = \left[\frac{W_{f,p} \sqrt{\Delta P_{f,p}} + W_{f,m} \sqrt{\Delta P_{f,m}}}{W_f} \right]^2 \quad (2)$$

Kinetic energy sharing:

$$W_f \Delta P_f = W_{f,p} \Delta P_{f,p} + W_{f,m} \Delta P_{f,m}$$

or

$$\Delta P_f = \frac{W_{f,p} \Delta P_{f,p} + W_{f,m} \Delta P_{f,m}}{W_f} \quad (3)$$

where $W_f = W_{f,p} + W_{f,m}$ for both cases.

The predictions of equation (1) above based upon the resultant fuel pressure drop values for the combined spray as per equations (2) and (3) above are plotted against the measured data for the 1 atmosphere, kerosine case in Figure 5. Clearly, the momentum approach is yielding significantly better agreement over the critical flow range during which the main spray is far from being well-formed.

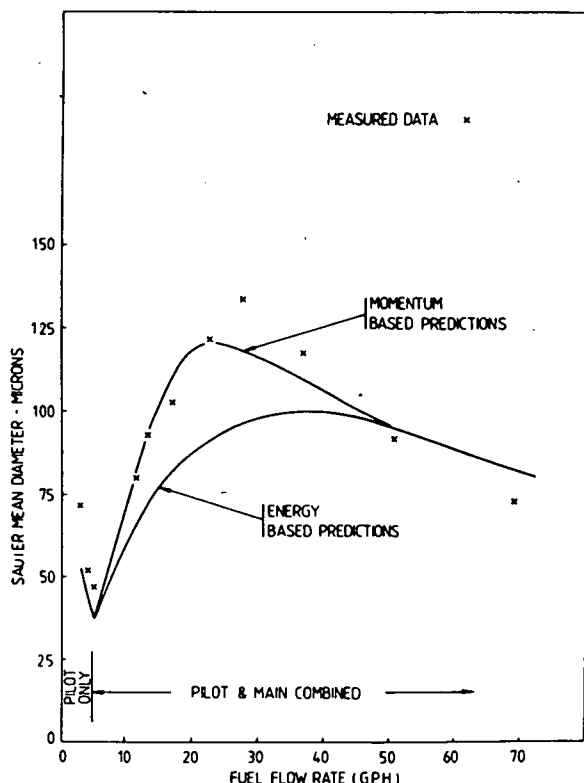


Fig. 5: Comparison of experimental drosize data with predictions

Kerosine, 1 atm

The approach of the pilot and main sprays sharing their momenta has also been discussed by Lefebvre, /13/, and he quotes specific expressions relating to the point of worst atomization. Whilst the point of poorest spray performance is clearly important from the standpoint of combustion-emission performance, it does not reflect adequately the prevailing state of affairs in view of the wide range of fuel flows over which the main spray is not fully developed.

Concluding Remarks

The results discussed in the foregoing section give an insight into the nature of interactions taking place between the pilot and the main sprays over a range of operating conditions. The spray quality and spatial distribution have been shown to be noticeably affected over a wide range of fuel flow through the main nozzle. The extension of the simplex pressure atomizer correlation to cover the dual-orifice injector is clearly a worthwhile development, but it does require a broad data base to evaluate its accuracy and applicability as a general expression. The design as well as the operational characteristics of the dual-orifice injector will vary from one engine application to another – as a matter of fact they sometimes do vary even within the same engine. The ratio of the main to pilot flow numbers, the relative cone angles, the pressurising valve settings, etc., would all be expected to influence the interactions taking place between the two sprays. The injector fuel flow-combustor air pressure relationship with engine type is an example of yet another related but unexplored variable.

The pressure of the air surrounding the fuel spray has been shown to exert a strong influence upon its behaviour. An increase in the density of air following a rise in air pressure, increases the magnitude of aerodynamic forces that are encountered by the liquid upon leaving the discharge orifice. This has a beneficial effect upon spray quality because it makes the process of fuel disintegration more intense. However, fuel distribution is adversely affected because of a reduction in penetration achieved by the liquid. In an engine, an increase in the combustion chamber pressure will also be accompanied by an increase in temperature. Besides affecting the density of the spray environment, this may also result in evaporation of some of the fuel particles.

The spray assessments reported here have been carried out in isolation – the effect of combustor aerodynamics having been overlooked. In the main this was due to considerations of cost and complexity. The effect of such air flows as injector shroud, primary zone swirler, secondary holes, etc., particularly upon spray ballistics could be profound and is clearly an avenue for further research. Air flow patterns within the combustion zone will vary depending upon the scale and intensity of recirculation and this in turn may influence the characteristics of the fuel spray.

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Effect of Injector Geometry Variables Upon the Spray Performance of a Plain-Jet Airblast Atomizer†

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ABSTRACT

This paper presents the results of a study into the effect that liquid orifice orientation and scale have upon the dropsizes performance of a plain-jet airblast atomizer featuring the injection of multiple liquid jets into a swirling airstream. Tests were conducted on water at near atmospheric pressure and temperature conditions using the well-established laser light scattering technique for spray quality measurements. The results presented in the paper reveal that the angular orientation of the liquid orifice, both in longitudinal and radial directions has a noticeable impact upon the atomization performance and exhibits scope for attaining further worthwhile reductions in dropsizes relative to the multiple, transversely injected liquid jet configuration.

LIST OF NOTATIONS

ALR air to liquid mass ratio
 d diameter
 $\dot{m}$ mass flow

† Amended version of paper presented at the Beijing International Gas Turbine Symposium (ASME) 1-7 September, 1985.

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P	pressure, atmospheres
$\Delta P/p$	atomizer air pressure drop, %
SMD	Sauter Mean Diameter, micron or m
T	temperature
V	velocity
α, β	liquid injection angles
γ	swirler vane outlet angle
η	absolute viscosity
ρ	density
σ	surface tension

Subscripts

a	air
l	liquid
o	orifice (injection)
j	jet (liquid)

1 INTRODUCTION

The importance of good quality fuel preparation is now widely acknowledged as being crucial to many performance aspects of gas turbine combustors. Specifically, characteristics such as ease of ignition (over a range of operating conditions from sea level to high altitudes); efficiency and stability; temperature distribution of the gases at the combustor exit; levels of smoke as well as of other noxious pollutants; amounts of flame radiation and its effect upon the durability of the combustor liner. Clearly the basic aim has to be to achieve the specific performance goals relating to a given system in terms of all these parameters and to maintain them in the event of a degradation in the quality of fuels whether derived from hydrocarbon or alternative sources. In addition, the trend towards an increase in gas turbine pressure ratios poses yet another level of complexity on the fuel injection/combustion system designers.

The superior performance of the airblast atomizer over the pressure jet type has led to its widespread adoption in the modern high pressure-ratio aircraft type of gas turbine engine. The important advantages of airblast atomization have been discussed in some considerable detail by Lefebvre.¹ From amongst the numerous airblast atomizer geometries that have been investigated over the years, two main types seem to stand out. These are the, so called pre-filming type,

investigated extensively by Lefebvre and his co-workers^{2,3} and the plain-jet type, the subject of this and other recent Cranfield studies.⁴⁻⁹

The key design feature of the pre-filming arrangement is the attempt to spread the liquid into a thin, continuous annular sheet of uniform thickness. The smallest sized drops being produced by the thinnest liquid sheet. This annular sheet, generated on a pre-filming surface, is then exposed to two high velocity airstreams. Intimate fuel and air contact is achieved by arranging for these two airflows to sandwich the thin liquid sheet. A drawback of this design philosophy is the need to provide for two separate airflow passages within the atomizer body, and this not only complicates the atomizer design, but also makes it more expensive.

Because of this the plain-jet type of airblast atomizer, wherein the liquid is not pre-filmed into a thin sheet but instead injected in the form of one or more discrete circular jets, is sometimes preferred. These circular liquid jets undergo disintegration in-flight in a single airstream, usually provided by a conventional swirler, to form a finely atomized spray. The extent to which the liquid and air interact effectively in the plain-jet configuration is dependent upon the geometric variables relating to the air swirler and the liquid injection orifice.

The purpose of this paper is to further extend the level of knowledge regarding the design aspects of the plain-jet airblast atomizer. Specifically it deals with the effect that the liquid injection orifice orientation and scale have upon its spray performance. Despite the fact that plain-jet airblast atomization has been studied fairly extensively, particularly in the last decade or so,⁴⁻⁹ little is known about the effect of atomizer geometry upon spray performance. In the main, earlier studies have tended to examine the effect of operating variables (i.e. air and liquid properties) upon the spray performance of atomizers of a given geometry without paying a great deal of attention towards the optimization of that geometry. The work reported here is an attempt to remedy some of these deficiencies and is a part of an on-going programme of research into plain-jet airblast atomization at the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. Further details relating to this study can be found in Ref. 6.

2 EXPERIMENTAL PROGRAMME

The primary variables selected for the purposes of this study were the angular orientation and scale of the injection orifice. The angular

orientation was varied in two planes—longitudinal and radial as can be seen in Fig. 1. In addition a limited amount of experiments featured the effect of such air properties as the velocity and air-to-liquid mass ratio. The effect of liquid surface tension and absolute viscosity were excluded from this programme due to the considerable depth to which they have been covered in the previous Cranfield studies.^{5,9}

The approximate range of conditions actually covered in the experiments are detailed below:

Airstream velocity	35–80 m/s approx.
Airstream density	Corresponding to normal pressure and temperature conditions.
Air-to-liquid mass ratio	1–10 approx.
Injection orifice l/d ratio	4 approx.
Injection orifice diameter	0.5 to 1.8 mm
Number of injection orifices	16

Angular orientation of injection orifices:

- (1) Longitudinal plane α_0 from -30° to $+45^\circ$
- (2) Radial plane β_0 from 0° to 60°

The atomizer examined in this investigation was similar in design to that used by Hussein⁵ and featured a curved vane air swirler with an outlet angle γ of 65° . The main difference being that Hussein's work on the complete atomizer (in contrast to the single jet studies that were also undertaken) featured the transverse injection of multiple liquid jets

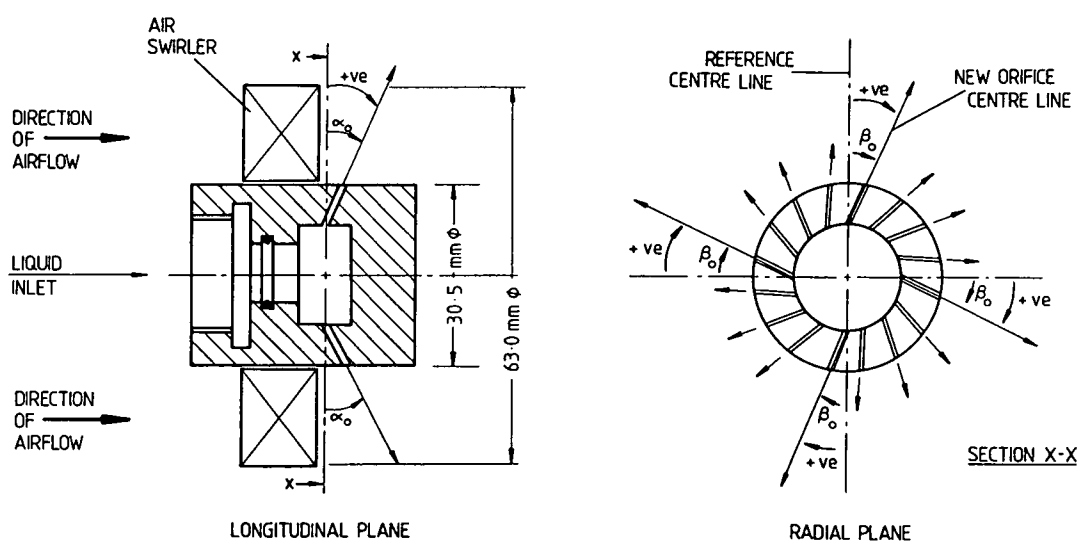


Fig. 1. Atomizer geometric variables.

whereas in the present work the angular orientation of the liquid jet array has been varied independently over a wide range in longitudinal as well as radial directions as shown in Fig. 1. A large number of atomizer heads were manufactured, each with a different angular orientation (longitudinal as well as radial) for the purposes of this study. It should be pointed out that these angular variations were carried out individually, i.e. either in the longitudinal or the radial direction but not in a combined longitudinal and radial direction.

3 EXPERIMENTAL DETAILS

A schematic illustration of the test facility is shown in Fig. 2. Air at near normal atmospheric pressure and temperature was supplied to a transparent circular test section through a bell mouth located in the settling chamber. The air mass flow was measured in accordance with the specifications of B.S. 1042. Detailed measurements of air temperature and velocity profiles were carried out and the profiles relevant to this study are presented in Ref. 6.

Water ($\eta = 0.001$, $\sigma = 0.0735$, $\rho = 1000$) was the only spray medium used in this study and was fed to the injector by means of a multi-stage pump. A bank of precision flowmeters, appropriately calibrated before

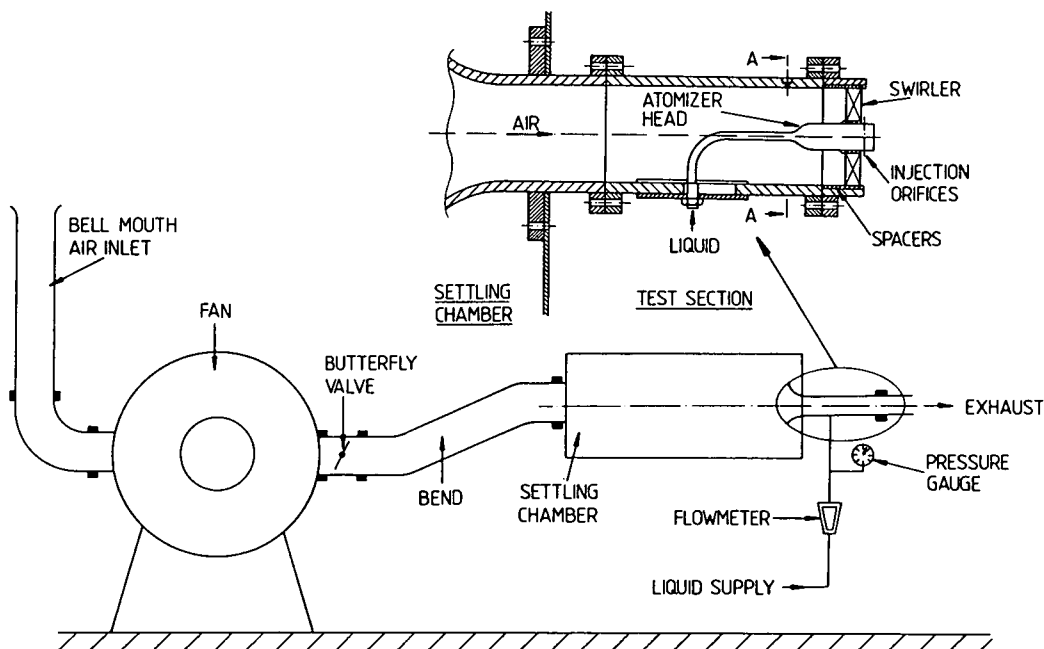


Fig. 2. Schematic diagram of test rig.

the commencement of the experimental programme, were used to establish the correct liquid flow conditions for the injector.

The spray Sauter Mean Diameters were measured using the well-established, non-intrusive, laser light-scattering technique. The optical technique is based upon the principles of forward diffractive scattering of a parallel, monochromatic beam of light as it passes through the test spray and has been used extensively for the earlier airblast atomization research.^{3,5} Generally speaking, the technique has been observed to yield satisfactory mean drops size results down to about 20 microns for a wide variety of fuel injector types as well as their operating conditions. To ensure the reliability of the experimental results, the optical bench was calibrated and checked for accuracy in operation by using a pressure jet type of Delavan injector of a known drops size performance.

For the type of experimental set up utilized in this study, Hussein *et al.*,⁸ established that the process of conversion of liquid into a multiplicity of drops is sensibly complete at a distance of some 50 mm from the point of injection, and that no significant coalescence occurs for some distance beyond it. Consequently, a measuring station located 70 mm from the injection orifices was chosen for the purposes of this study.

4 RESULTS

The effect of air to liquid mass ratio upon spray quality, over a range of airstream velocities, is depicted in Figs 3 and 4 for two different angular

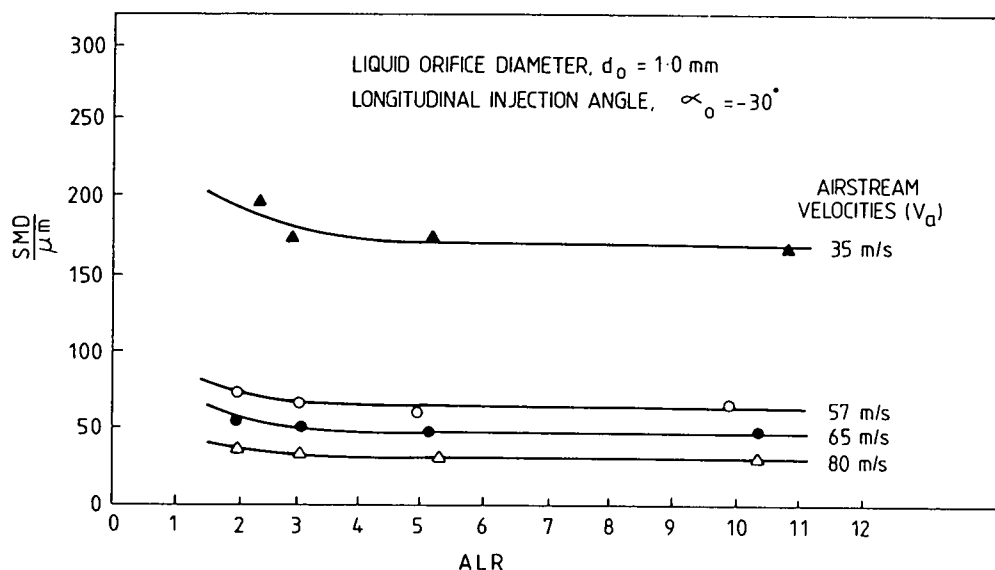


Fig. 3. The effect of changes in air to liquid ratio on SMD characteristics, $d_o = 1.0 \text{ mm}$.

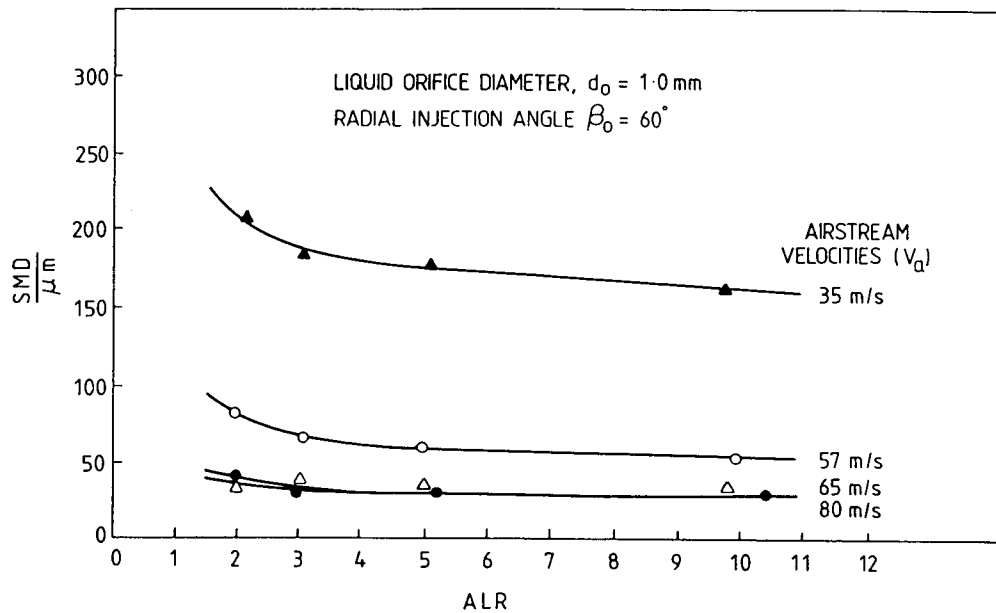


Fig. 4. The effect of changes in air to liquid ratio on SMD characteristics, $d_o = 1.0$ mm.

orientations of the injection orifice. It is clearly evident that changes in air to liquid ratio do not have a strong influence upon the quality of the spray especially for higher airstream velocities. This observation is similar to that reported in Ref. 9 and underlines the importance of ensuring that such atomizers are designed to operate with an ALR of about 2 to 3 due to considerations of atomizer size/cost, and to a somewhat limited extent due to weak combustion stability. Also evident from the same figures is the effect of airstream velocity upon the fineness of the liquid spray. As would be expected, on the basis of the previously established trends, an increase in airstream velocity from 35 to 80 m/s results in a significant reduction in the spray mean dropsize values.

Figures 5 and 6 illustrate the effect of varying the angular orientation of the injection orifice in the longitudinal direction for 1.0 and 1.8 mm orifice diameters. Clearly the angle at which the jet of liquid is injected into the high velocity airstream can have a noticeable effect upon the duration as well as the effectiveness of liquid and air interaction. Upstream injection (i.e. negative values of α_o) would be expected to yield a more vigorous interaction with the airstream relative to the downstream (i.e. positive values of α_o) injection. Results presented in Figs 5 and 6 confirm this particularly at lower levels of airstream velocity. It is abundantly clear that the transverse injection of liquid ($\alpha_o = 0^\circ$) will result in vastly superior spray quality relative to the co-axial, co-flowing configuration ($\alpha_o = 90^\circ$).

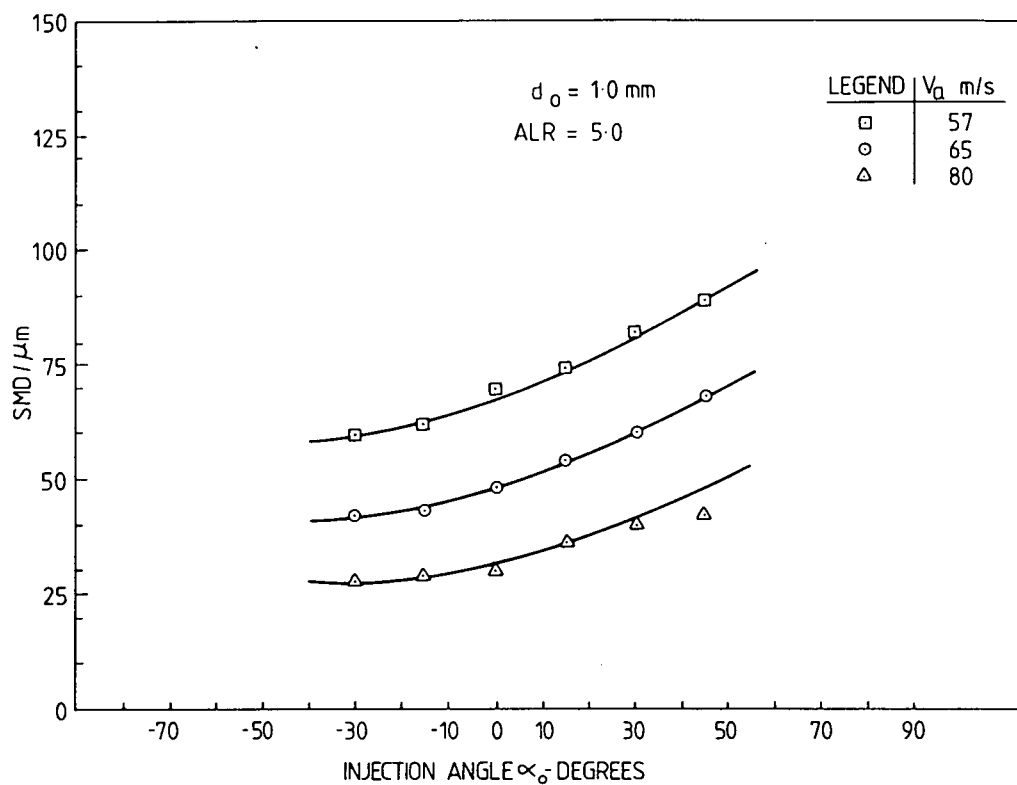


Fig. 5. Variation of SMD with longitudinal injection angle (α_0), $d_0 = 1.00 \text{ mm}$.

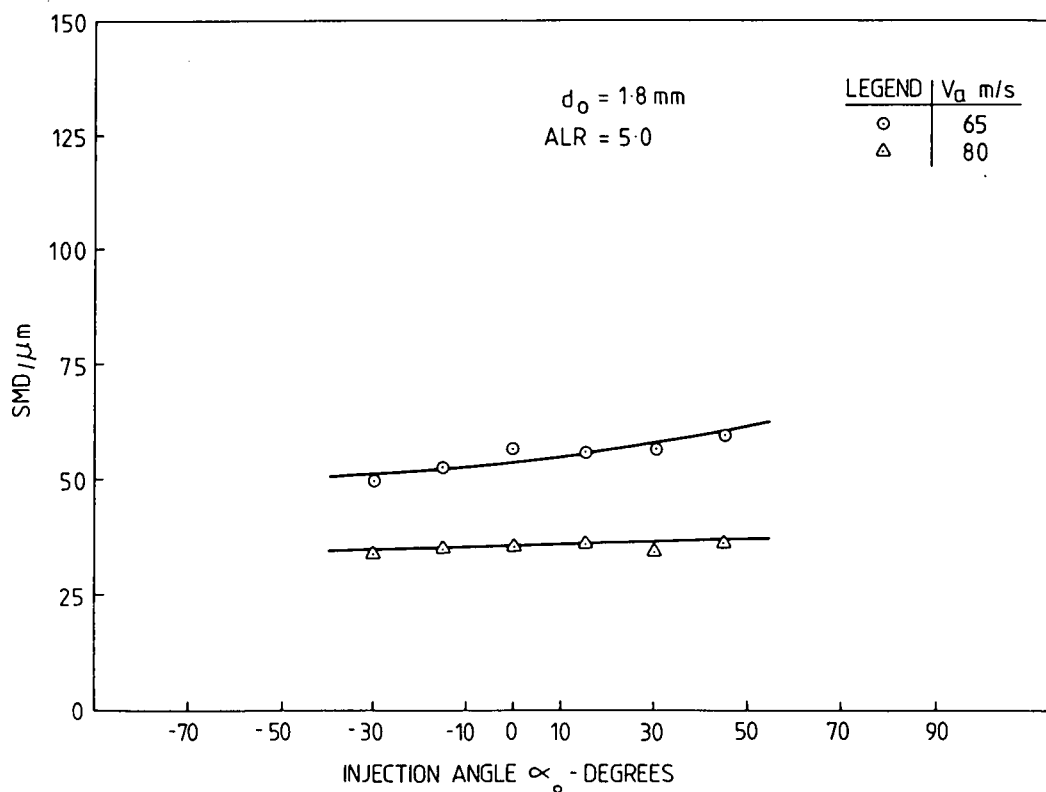


Fig. 6. Variation of SMD with longitudinal injection angle (α_0), $d_0 = 1.8 \text{ mm}$.

The influence of varying the angular orientation of the injection orifice in the radial direction for 1.0 and 1.3 mm orifice diameters is depicted in Figs 7 and 8 respectively. It is clear from these figures that the effect of these angular orientation variations upon spray mean dropsiz becomes less significant as the airstream velocity increases. In fact for an airstream velocity of about 80 m/s, the variation of the injection configuration in the radial direction has virtually no effect upon the atomization quality. Since airblast atomizers tend to suffer from somewhat poor spray performance during the start-up phase featuring low airstream velocities, careful attention to the angular orientation in the radial direction may help to ameliorate this to some extent. This improvement in dropsiz performance at low air velocities is a result of improved physical contact between the liquid jet and the airstream. Radial injection angle change results in simultaneous changes in the liquid trajectory/path length within airflow, the degree of counterflow imparted to liquid at the point of exit and, the local geometry induced interactions—for example the proximity of swirler vane wakes etc. Whilst still photography was used to obtain broad

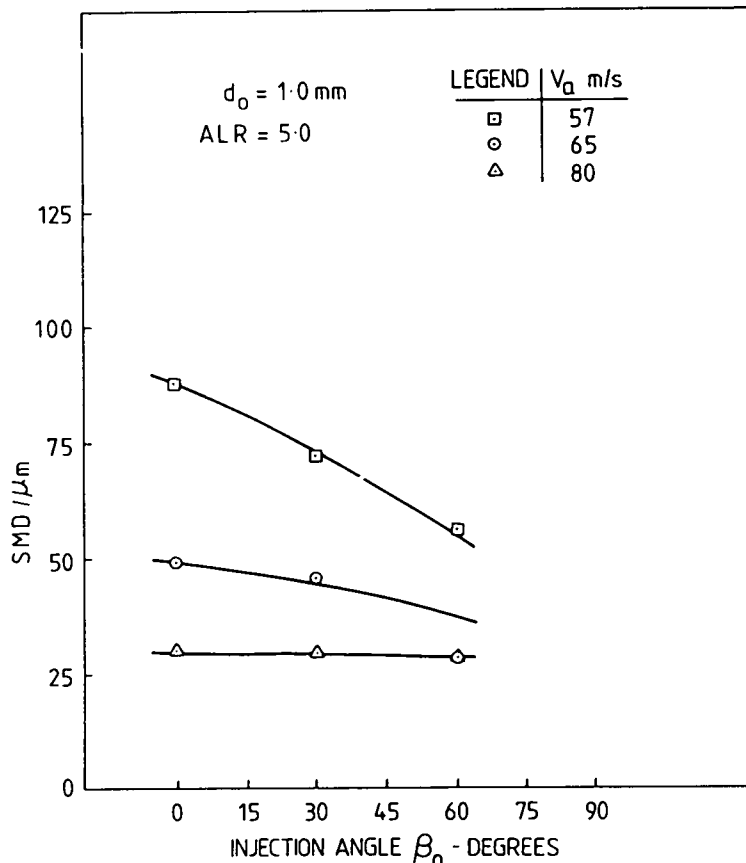


Fig. 7. Variation of SMD with radial injection angle (β_o), $d_o = 1.0 \text{ mm}$.

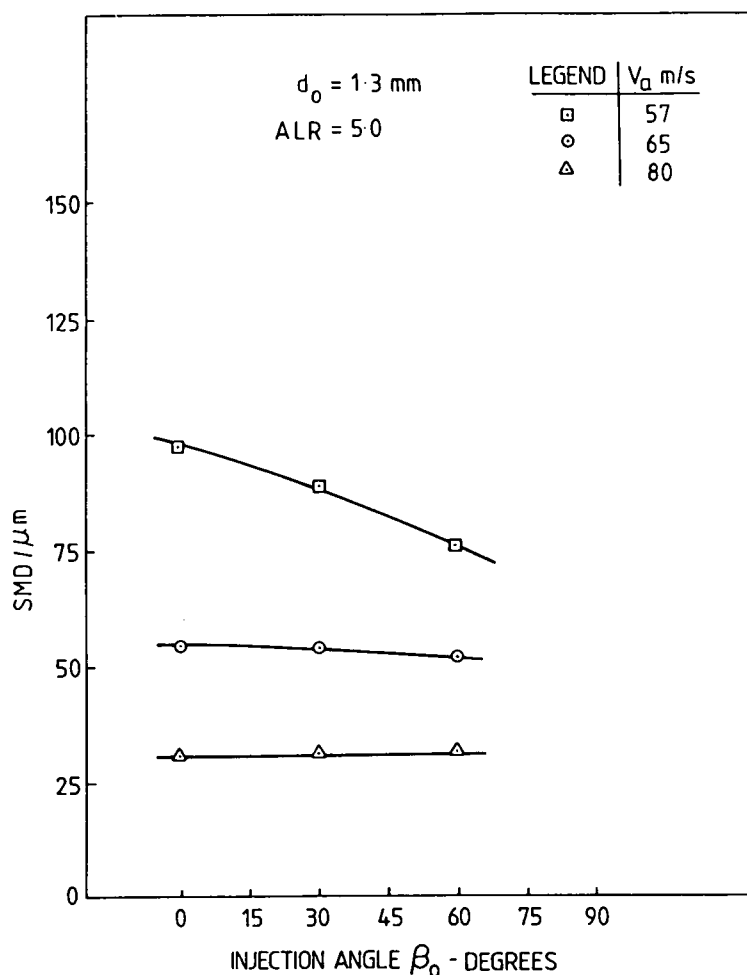


Fig. 8. Variation of SMD with radial injection angle (β), $d_o = 1.3 \text{ mm}$.

insight into the spatial/conical distribution of liquid, it did not provide answers to the relative importance of the various changes triggered by variations in β_o . Further work is needed to shed more light on this particular aspect of plain-jet airblast atomization.

Figures 9 and 10 illustrate the effect of varying the diameter of the liquid injection orifice upon spray mean drops size for $\alpha_o = -30^\circ$ and $\beta_o = 60^\circ$ respectively. In both the instances, an increase in the size of the injection orifice has a degrading influence upon the atomization performance, particularly at lower levels of airstream velocities. It may be argued that for a fixed liquid flowrate a change in the size of injection orifice will be accompanied by a change in the velocity at which the water is injected and this in turn may partly be responsible for the change in spray performance. It has been shown elsewhere¹⁰ that, in general, the liquid injection velocity has little effect upon the mean drops size performance of plain-jet airblast atomizers. The liquid

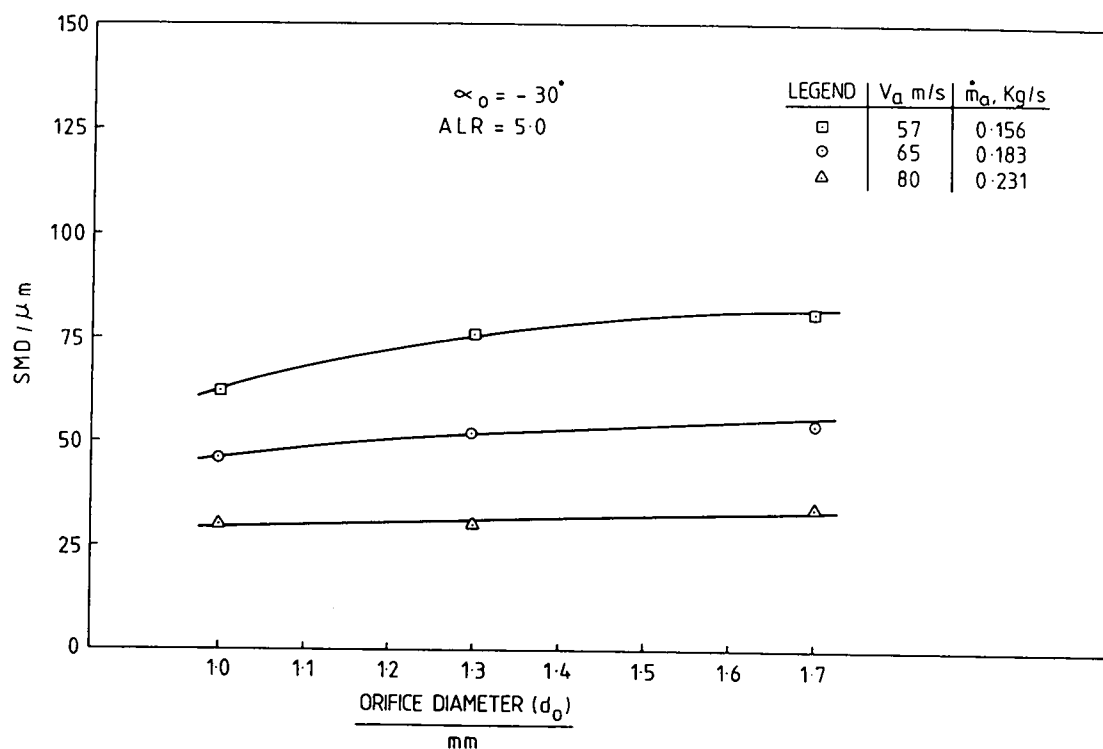


Fig. 9. Variation of dropsiz with orifice diameter where $\alpha_o = -30^\circ$.

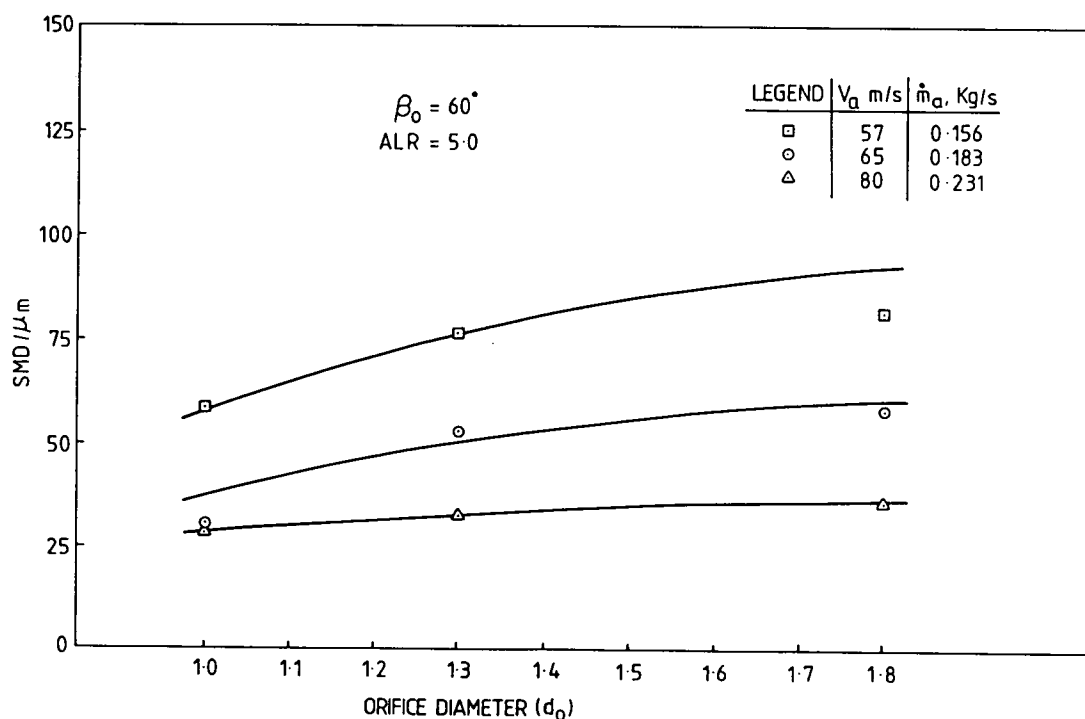


Fig. 10. Variation of dropsiz with orifice diameter where $\beta_o = 60^\circ$.

injection velocity has been estimated to drop from about 2.5 m/s to about 1 m/s as the diameter of the orifice is increased from 1.0 to 1.7 mm for the 57 m/s airstream velocity curve of Fig. 9. Such a miniscule change in liquid injection velocity is not likely to affect the spray performance significantly. In other words it is largely the change in scale of the characteristic dimension (i.e. the injection orifice) that is responsible for the change in spray quality.

5 ANALYSIS OF RESULTS

The primary objective for this study was an examination of the effects of angular orientation and size of the injection orifice upon spray quality. Effects of airstream velocity and air to liquid mass ratio were explored on a somewhat limited scale. The influence of liquid properties such as viscosity, surface tension and density has, however, not been covered here since water was the test medium for all experiments.

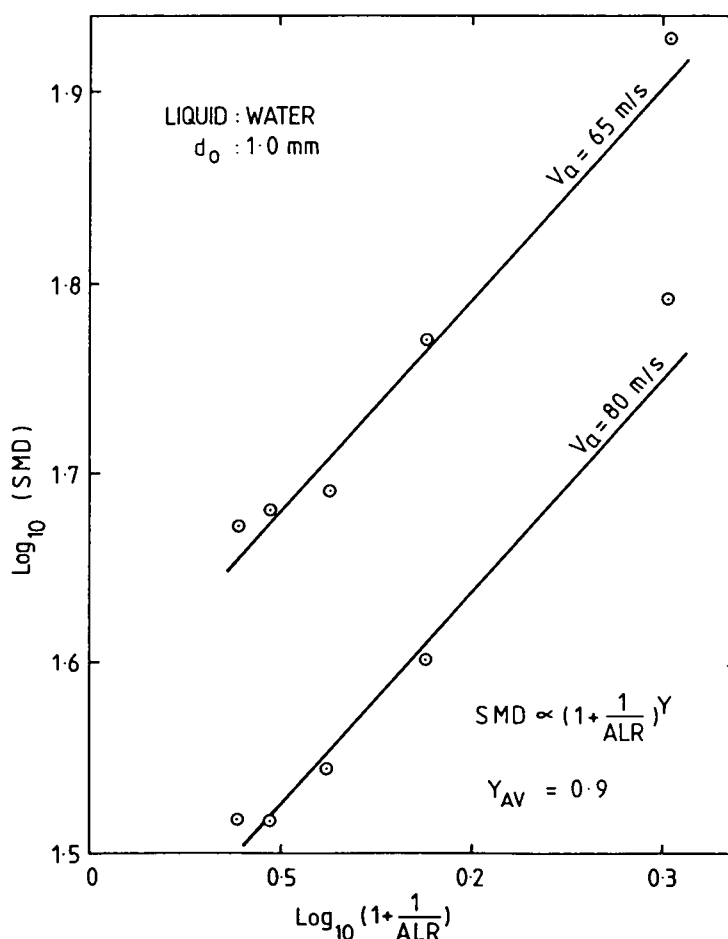


Fig. 11. Correlation for variation of SMD with ALR $\alpha_o = \beta_o = 0^\circ$.

The geometry of the air swirler is yet another related but unexplored variable. This effectively limits the development of a detailed and reliable empirical correlation. However, the analysis of the dropsiZe data relating to the scale of the injection orifice, the airstream velocity and the air to liquid ratio has been performed using the conventional log-log analysis methodology (see Figs 11 and 12 for example) to yield the following relationships:

(1) $SMD \propto (1 + 1/ALR)^{0.9}$

(2) $SMD \propto \frac{1}{V_a^{1.09}}$

(3) $SMD \propto d_o^x$

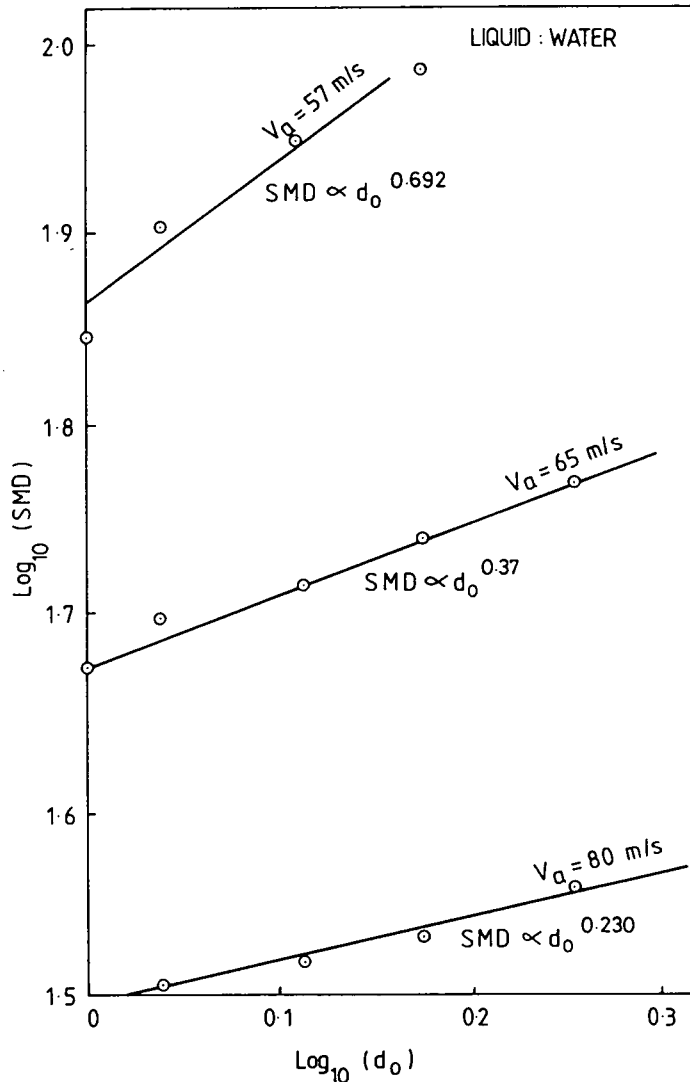


Fig. 12. Correlations for variation of SMD with d_o $\alpha_o = \beta_o = 0^\circ$.

where x takes the values of 0.23, 0.37 and 0.69 for airstream velocities of 80, 65 and 57 m/s respectively.

The exponents relating to the air to liquid mass ratio and airstream velocity terms above are in good agreement with those that have most recently been reported in the research literature—for example see Refs 3 and 9. The index x for the d_o term, however, changes with airstream velocity. Hussein⁵ proposed an average value of index x of 0.477 for his data and this agrees well with the average of 0.43 in the present study. However, the information available on this particular aspect is limited and further work needs to be undertaken to establish more fully the relationship between d_o and SMD particularly over a wider range of liquid viscosity than has been covered in this investigation.

6 CONCLUSIONS

The basic conclusions that can be drawn from this work are as follows:

- (1) The angular orientation of the liquid jet in the longitudinal as well as the radial direction has a noticeable effect upon the spray mean droplet performance of the plain-jet airblast atomizer. Results indicate that there is scope for further reductions in droplet size relative to the multiple, transversely injected liquid jet configuration.
- (2) Combined longitudinal and radial orientation of the injection orifice is worthy of further study especially to further improve the spray performance at low air velocities of the type encountered during start-up phase.

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SPRAY PERFORMANCE OF A VAPORISING FUEL INJECTOR

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SUMMARY

The purpose of this paper is to examine the spray performance of a vaporiser fuel injector of a type that has accumulated extensive service experience in sub- and supersonic commercial and military aircraft applications. Spray performance data covers a wide range of operating conditions including the effects of fuel quality as well as the atomizing air temperature. The chief objective is to further not only the current level of understanding regarding the fundamental functional aspects of vaporiser technology but also the data base for future designs.

INTRODUCTION

Effective fuel-air mixture preparation is now widely recognised as being of paramount importance in order to achieve satisfactory combustor performance. This is acknowledged to be the case in the context not only of the current but to an even greater extent for the future generation of gas turbine engines with their inherently more demanding operational requirements of pressure, temperature, fuel flexibility/flow range and pollution control. The mechanism through which bulk fuel is transformed into a spray of droplets and the factors influencing their behaviour need to be well understood if sprays featuring optimum characteristics as well as satisfactory interaction with the combustor primary zone environment are to be generated. This has resulted in a considerable amount of research activity in recent years focusing attention upon the structure of spray emanating from fuel injectors. However, with very few exceptions (Refs 1-3) these studies have been restricted to pressure and airblast atomised sprays, largely at ambient air conditions.

This paper is devoted to an examination of the spray performance of a vaporising fuel injection system of a type that has been used extensively by Rolls-Royce in sub- and supersonic commercial and military aircraft applications. The modern annular vaporising chamber concept depicted in Figure 1 is fully described in Ref 4. The continuing effectiveness of the vaporiser is demonstrated by its having achieved substantial trouble-free service life, 2300 hours to date, in the Olympus 593 engine featured in Concorde. Confidence in its future is illustrated by its current use in the RB199 engine in Tornado as well as by its selection for the EJ200, the Euro Jet Fighter for the next century. Whilst the vaporising fuel injector has demonstrated highly competitive combustion/emissions performance thus far, its projected useage under more arduous conditions of operation has prompted a thorough re-appraisal of the fundamental functional aspects of vaporiser technology.

It transpires that the corridor of satisfactory vaporiser operation (eg. adequate mechanical integrity without significant smoke, carbon accretion etc) narrows with increasing compressor exit temperature. Extreme caution therefore needs to be exercised in the selection of the air-to-fuel ratios (AFR) that the vaporiser is designed to operate with, especially at fuel rich conditions. Of particular relevance to the design process is the development of an in-depth understanding of the mechanistic as well as the operational behaviour of the vaporising injector through a series of well-planned and executed experiments under non-combusting and combusting conditions. Some of the results pertaining to the vaporiser efflux obtained during the course of such studies are the subject of this paper.

EXPERIMENTAL

At the very outset it was felt that the use of imaging cum laser diffraction techniques should prove beneficial in obtaining experimental data that would shed adequate light on the mechanistic/operational behaviour of the vaporising style of fuel injector. Short duration spark photography was expected to identify the character of the efflux at the point of exit from the vaporiser tubes under non-combusting and combusting conditions whereas the laser diffraction technique was to provide quantitative information regarding the spray structure vis-a-vis the drop size. Furthermore, the well established, non-intrusive nature of the two techniques selected for experiments offered the prospect of meaningful and reliable results.

The test hardware and experimental technique employed in the spark photographic investigation were largely as described in Ref 1. A single vaporiser sector cut from a typical annular combustor was fitted with transpiration cooled sidewalls and modified to permit optical access to the vaporiser efflux zone (figures 2,3). A heat exchanger was installed in the vaporiser fuel delivery line to enable the fuel temperature effects to be investigated in this study.

The argon arc light source and associated optics provided a parallel beam of light which illuminated the spray for a duration of approximately 300 ns and a focused shadow of the 'frozen' efflux was cast in the plane of the film. The current exercise featured a light source of increased power (ca. X1.5) to that of the Lunartron unit used in the previous tests - thus offering the prospect of more reliable data. The shadowgraphy technique was applied to combusting and non-combusting effluxes at air pressures upto 1300 kPa.

The experimental set up utilised for spray drop size measurements was similar to that used in Ref. 5. Non-vitiated, hot air was generated by using electrical resistance heating in combination with counter-flow type of heat exchanger unit connected to a kerosine fired slave combustor. The mass flow of hot air that was surplus to requirement bypassed the vaporiser working section. An orifice plate to BS1042 was installed as close as practically possible to the measurement section to enable the air mass flow monitoring. A thermocouple was located just upstream of the vaporiser air inlet. Air pressure drop across the vaporiser was measured by a manometer and all drop size tests were carried out at near atmospheric pressure.

The vaporiser as well as the fuel injector geometry for the drop size study was basically identical to that deployed for the spark photographic assessment. The fuel supplied to the injector was at ambient temperature and the relevant flow conditions were achieved by using calibrated flow meters.

Spray drop size measurements were carried out by utilising a commercially available particle sizer - Malvern Instruments Model 2200. Briefly, the instrument is based upon the well established principle of diffractive scattering of a collimated, coherent and monochromatic beam of light in the forward direction as a result of its passage through the test spray. The instrument uses a Helium - Neon laser as the light source while a multi-element, concentrically configured, semi-circular ring detector monitors the scattered light signals. Through a process of iteration a dedicated microcomputer arrives at a drop size distribution that exhibits a computed light energy distribution close to that actually measured. The computed versus measured light energy distribution comparisons can be performed for a range of assumed drop size distributions - notably Rosin - Rammler, log - normal, model - independent, etc.

In house and commercially developed light diffraction instruments have been used extensively for gas turbine fuel spray research in recent years. Drop size data reported in the open literature, thus far however, has been confined mainly to injectors spraying in ambient air conditions due to considerations of cost and complexity. Some exposure had nevertheless, been achieved in the use of such optical techniques for twin-fluid atomised spray studies in elevated air pressure environments (Refs. 6 and 7). By contrast there was almost a total dearth of similar exposure to twin-fluid atomised spray studies under conditions of elevated air temperature. Preliminary tests with hot air revealed the pattern of light scattering in the proximity of the optical axis to be significantly different from that for the ambient temperature tests. This change in light scattering pattern was observed to follow the air temperature, increasing with an increase in air temperature and vice versa. Furthermore, the problem seemed to be just as severe even in the absence of liquid fuel injection. From analysis of the scattering data, it became apparent that the laser beam was being diffused/steered in the vicinity of the optical axis. Refractive index variations resulting from temperature gradients are responsible for the generation of additional scattering cells. Consequently, the overall scattering pattern is a combination of that due to liquid droplets as well as the thermal effects. The procedure adopted during the tests was to record the background light scattering levels at each of the working temperatures in the absence of liquid fuel injection as the reference. This was followed by the test run wherein the fuel was injected and the subsequent drop size analysis took account of the background light levels at the relevant air inlet temperature thus effectively countering the beam steering problem.

Effects of fuel quality upon vaporiser performance were confined in both studies to aviation kerosine and gas oil. Relevant properties of the two fuels are listed in table 1.

RESULTS AND DISCUSSION

The primary objective of the parametric exercise reported here was to study the effect of air, fuel and injector variables upon vaporiser performance in a combusting and non-combusting environment. This was expected to improve not only the level of knowledge regarding the detailed structure of the two-phase efflux emanating from the vaporising fuel injector but also the design capability for future applications. Furthermore, the availability of such experimentally determined representative data could also enhance the prospect of its being usefully correlated with some key aspects of combustion performance.

Spray Imaging

This technique is generally capable of detecting the very high frequency variations to which all fuel injectors are subjected. The photographs presented in this paper feature a magnification of approximately three and give a good account of the average situation at each test condition. The zone illuminated by the spark is shown in figure 3.

Effect of Combustion

The comparison made between the effluxes at non-burning (no vaporisation situation) and burning conditions, plate 1(a) and 1(b) respectively, highlights the significance to fuel preparation process of the heat transfer from the reacting gases to the vaporiser walls. A detailed semi-empirical assessment of the external heat transfer processes with allowances for turbulence enhancements of the convective and radiative fluxes inferred an upper limit of 50 percent for the degree of vaporisation at this burning condition. This is borne out by the experimental results.

Effect of Fuel Temperature

Fuel temperatures significantly higher than ambient occur at all engine conditions as a result of the fuel being used as the coolant medium in lubricating oil coolers. The effect this has on the fuel preparation process within the vaporiser at idle conditions is also evident in Plate 1,(b) versus (c). A comparison between plates 1(c) and 1(a) reveals the degree of vaporisation under combusting conditions with hot fuel to be of the order of 80 percent. This is broadly in line with the predicted value at these conditions.

Effects of Vaporiser AFR, Inlet Air Temperature

It is clear from Plate 2 that increases in AFR have a beneficial influence upon the spray quality. Since such improvements are translated into higher combustion efficiencies and lower smoke/carbon levels it is extremely important that as high a vaporiser air throughput as is compatible with integrity should be employed.

Similarly, the degree of vaporisation and fineness of the spray improve with increasing inlet air temperature (Plate 3). Provided that the air temperature is above the boiling range of the fuel at a given pressure, this mechanism of fuel heating is very effective considering the short residence times involved. These results suggest an intimate physical contact between the fuel and air within the vaporiser. This is a direct consequence of the complex internal aerodynamics (see plate 4) necessary to ensure that all internal surfaces of the device are well scrubbed by the two phase mixture (Ref. 8).

Effect of Pressure

The spark photographic investigation has been extended to examine the vaporiser efflux at high pressures. As expected the mottled background (schlieren effect seen in all combusting effluxes) became increasingly dense at higher pressures eventually causing a degree of obscuration beyond which no useful information could be derived by this approach. The working range of the technique was thus defined as between ambient pressure and 1300 kPa.

The efflux for a typical AFR and inlet air temperature at this pressure limit is presented in Plate 5. Although the ability of the technique to detect droplets at these pressures is unknown, it is fair to claim a high degree of vaporisation at this condition bearing in mind that here there is a four-fold increase in fuel flow over the idle condition.

From a simple analysis of the two phase flow through the device at these conditions it is clear that the heat energy of the airstream alone is sufficient for this to be the case. Autoignition precluded comparisons of burning and non-burning effluxes at this pressure.

A very modest carbon accretion on the vaporiser outlet is evident at this condition.

Effect of Injector Geometry

The 4-jet fuel injector was conceived as a solution to the problem of potentially damaging thermal gradients resulting from the deletion of stem cooling air on the Olympus 593 vaporiser (Figure 4). Although its introduction in service has not proven necessary with the identification of improved materials, this fuelling arrangement may make a worthwhile contribution to gaseous emissions and smoke/carbon control at more arduous operating conditions.

An investigation of its effect on efflux quality (Plate 6) confirmed the potential benefits of doubling the number of fuelling points. The more even fuel coverage of the vaporiser stem walls is translated into an improved fuel distribution at the outlet and furthermore at high inlet air temperatures the more intimate fuel/air contact is reflected in higher degrees of vaporisation relative to the standard 2-jet system. Such improvements in fuel preparation prior to combustion may prove necessary to maintain smoke and carbon deposition at acceptable levels for advanced cycle engines.

Effect of Fuel Quality

It is desirable that the vaporising fuel injector exhibits satisfactory fuel flexibility/multi-fuel capability to adequately cope with the potential concerns regarding the quality of gas turbine fuels in future as well as under emergency situations. Consequently to determine the sensitivity of the vaporiser fuel preparation process to fuel type, efflux measurements were made while burning a poor quality gas oil. A direct comparison with the performance on standard aviation kerosine is made in Plate 7. From a simple calorimetric viewpoint, the lower degrees of vaporisation seen with the gas oil are not surprising. However, it has been demonstrated recently in a series of alternative fuel engine tests that the penalty incurred in idling efficiency as a result of such a deterioration in spray quality is less than 0.05 percent.

An important point to note is that at the engine idle condition (Plate 7, Condition A) no evidence of carbon deposition on the vaporiser is seen with the gas oil. Furthermore, boroscope inspections of the engine combustor after extended running on similar and even poorer quality fuels over the entire operating range revealed no significant carbon accretion on the vaporiser or anywhere else within the combustor. It was discovered possible, however, to generate substantial deposits on the vaporiser stem and outlet tube at certain conditions not encountered during engine operation (Plate 7, Condition B). The level of deposition shown represents an equilibrium situation.

The overall impression that emerges from the spark photographic work and engine test programme is that the vaporising combustor is remarkably insensitive to fuel type.

Dropsiz Measurements

Before the main investigation could proceed, the location of the drop size measuring station had to be selected carefully in order to ensure meaningful results. Measurements that are made too close to the vaporiser outlet will be misleading because the mechanism of droplet/spray formation will not have proceeded to its natural completion. Equally, measurements too far downstream from the outlet will also be unsatisfactory due to the possible influence of such secondary effects as droplet coalescence and evaporation. Experimental data in this study was obtained at two stations located some 3 and 6 centimetres from the vaporiser outlet. The 3 centimetre station was relevant to the combustor head/vaporiser geometry while the other station was selected to ensure compatibility with the bulk of other work carried out at the spray laboratories. Drop size data relating to the 3 centimetre station is presented in the subsequent sections while reference 9 features the full data.

Effect of AFR

Figure 5 depicts the influence that the vaporiser AFR has upon its Sauter Mean Diameter (SMD) performance for a range of air inlet temperatures with kerosine as the spray medium. An increase in vaporiser AFR can be observed to result in an improved spray quality, although the degree of improvement diminishes at higher levels of air inlet temperature as well as AFR. This reinforces the spark photographic study finding that higher values of AFR are conducive to the attainment of improved combustion performance. From these results it is evident that caution needs to be exercised in selecting the design point AFR. Excessively large values of AFR may result in some of the additional air not actually contributing to improved spray/combustion performance along with the added risk of thermal distress at high power conditions.

Effect of Air Pressure Drop

Engineers are faced with the perennial demand of having to design gas turbine combustors that will operate satisfactorily with a minimum of air pressure drop. This in turn requires that careful attention be devoted to the vaporiser air flow features in order to achieve the best possible level of spray performance that is compatible with required degree of wall cooling. Figures 6 and 7 illustrate the influence that vaporiser air pressure drop has upon spray quality. Clearly, the higher the available air pressure drop the superior the drop size performance although the degree of this superiority can be seen in both the figures to diminish somewhat at higher levels of air inlet temperature. Both the above performance trends are, generally speaking, akin to those already established for conventional air blast atomisers (Ref. 6,7).

Effect of Air Temperature

The influence of air temperature on mean drop size is shown in figure 8 where SMD is plotted against vaporiser inlet air temperature for a range of AFRs at a constant air pressure drop of 5 percent. Higher air temperature can clearly be seen to yield significantly finer sprays.

Such a powerful effect of air temperature upon mean dropsiz performance is in agreement with the findings of the imaging study. The airblast atomisation study of Rizkalla and Lefebvre (Ref. 10) is the only other attempt, to the best of the authors' knowledge, at exploring the effect of air temperature upon twin-fluid atomised spray quality. However, their work was limited to a maximum air temperature of 424°K and the interpretation of results somewhat difficult due to the combined variations in AFR and air inlet temperature. Furthermore, they made no comment whatsoever regarding the problem of beam steering. Their results showed a linear increase in SMD when the air temperature was raised in conjunction with a reduction in AFR. In view of the

foregoing, however, it is perhaps inappropriate to draw comparisons between the two studies. In general though, the effect of air temperature upon spray quality would be expected to be somewhat stronger for the vaporising type of fuel injection system relative to the air blast due largely to the considerations of residence time and internal aerodynamics.

Effect of Fuel Quality

Figure 9 illustrates the effect of fuel quality upon vaporiser mean drop size performance over a range of inlet air temperatures. At air temperatures close to ambient, the change in spray media from kerosine to gas oil leads to an increase in SMD due largely to an increase in absolute viscosity alone - the effects of changes in surface tension, density and distillation range being relatively insignificant. As the air temperature rises, the difference in spray quality is a consequence of the combined influence of absolute viscosity and distillation range differences. These results do not, however, provide an insight into their relative importance from the viewpoint of SMD. On the face of it, the viscosity sensitivity of the vaporising fuel injector at air temperatures close to ambient does not appear to exhibit any marked difference relative to that observed for airblast systems. Furthermore, the vaporiser fuel injector is free from small orifices which may be prone to blockage due to gumming while operating on poorer quality fuels.

Effect of Injector Geometry

As stated before, the modified 4 jet fuel injector of figure 4 offers the prospect of reducing thermal gradients in the inlet section of the vaporiser tubes relative to the basic 2 jet injector. Figure 10 allows a comparative assessment of their spray performance at two different levels of air pressure drop. As might be expected and indeed observed in the imaging study the 4 jet injector is exhibiting a somewhat superior drop size performance as a result of more intimate fuel and air interaction. This is backed up by liquid film studies that show a more even coverage of the inside walls in the vaporiser inlet stem area (Ref. 9).

CONCLUDING REMARKS

The choice of imaging cum laser diffraction techniques for examining the spray performance of the vaporiser fuel injector has turned out to be a satisfactory one. A testimony to that effect is provided by the foregoing sections of the paper that feature detailed and extensive experimental data covering a wide range of combusting as well as non-combusting conditions. The two techniques complement each other to yield a balanced insight into the phenomenological as well as the operational behaviour of the vaporiser - thus helping to advance significantly the state of knowledge regarding this style of fuel injector. Many of the uncertainties have been minimised if not entirely dispelled.

The results presented in this paper reveal that despite its mechanical and geometric simplicity, the vaporising fuel injector achieves high degrees of atomization, vaporisation and pre-mixing at engine idle conditions. Extension of these results to higher power conditions as typified for example by take off air pressures and temperatures would indicate further improvements in mixture preparation. In addition, the vaporiser seems to be remarkably insensitive to fuel type - coping admirably with gas oil.

The vaporising fuel injector exhibits spray performance trends that are generally similar in character to those already observed on conventional airblast atomizers - for example an improvement in spray quality with increases in AFR and air pressure drop whilst an increase in fuel viscosity having a somewhat adverse effect. A noteworthy exception to this general similarity being the stronger influence exerted by the air temperature upon the dropsize performance of the vaporiser due largely to considerations of residence time and internal aerodynamics. It is hardly surprising therefore, that the vaporising fuel injector is able to deliver highly competitive combustion/emissions performance.

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ACKNOWLEDGEMENTS

The loan of Malvern Particle Sizer by Ruston Gas Turbines Ltd. for the dropsize study as well as the support and interest of those individuals who have made this paper possible is gratefully acknowledged. One of the authors (AKJ) wishes to thank the Institution of Mechanical Engineers for the award of a travel grant in connection with the paper presentation.

TABLE 1

PROPERTY	KEROSINE	GAS OIL
Density in kg/m^3 at 15°C	797	863
Absolute Viscosity in Ns/m^2 at 15°C	0.0013	0.0053
Surface Tension in N/m at 20°C	0.027	0.0299
Distillation Range, $^\circ\text{C}$	152-236	188-342

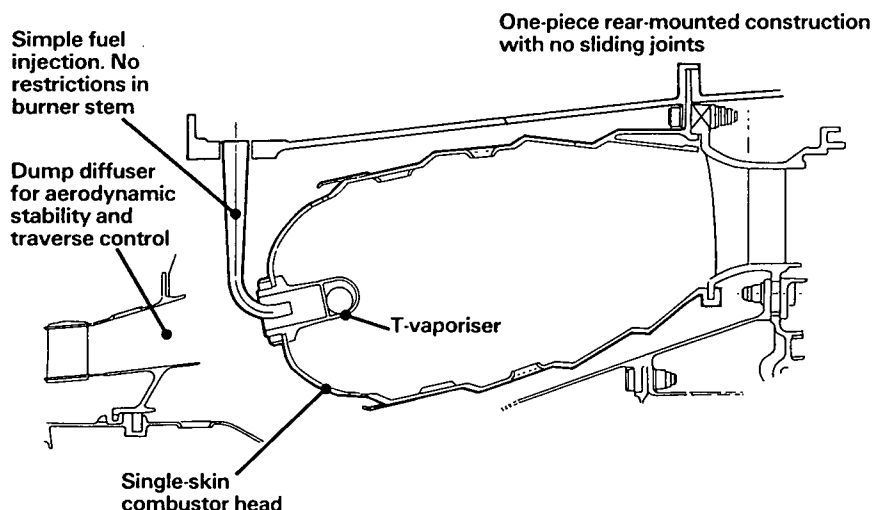


FIG. 1 ANNULAR VAPORISING CHAMBER

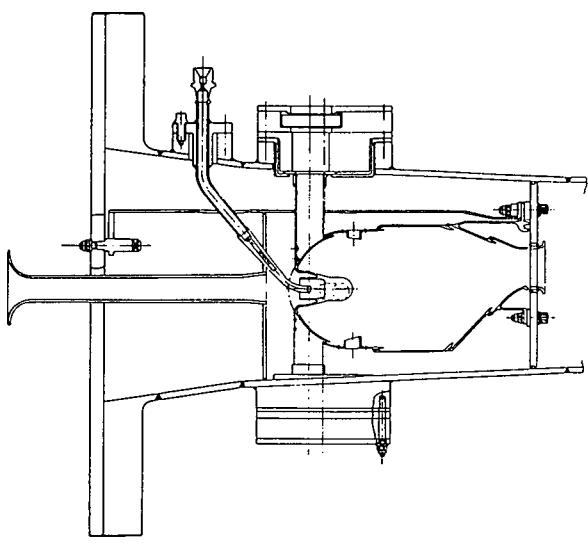


FIG.2. TEST UNIT

FIG.3.

ZONE ILLUMINATED BY SPARK

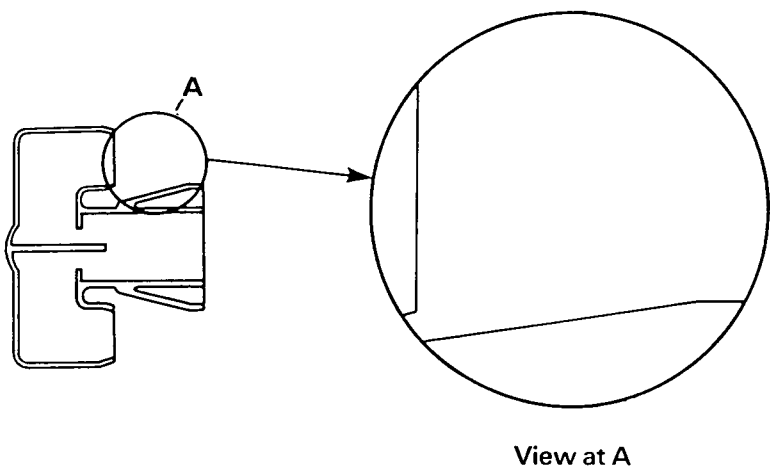
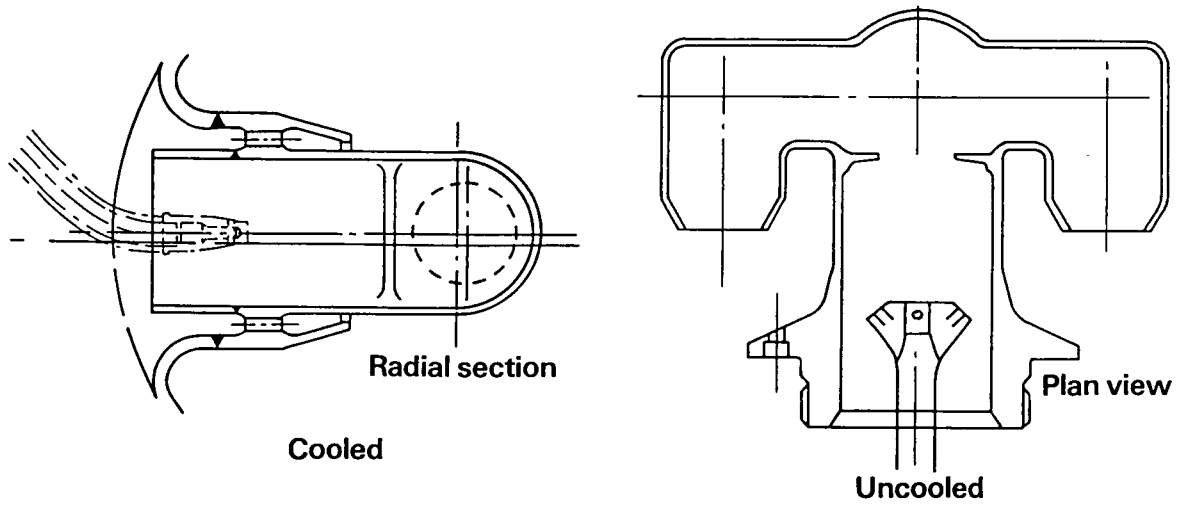


FIG. 4 VAPORISER CONFIGURATIONS

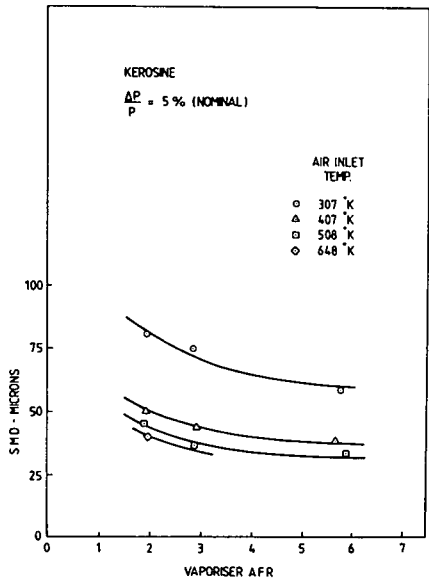


FIG. 5. EFFECT OF VAPORISER AFR UPON DROPSIZE

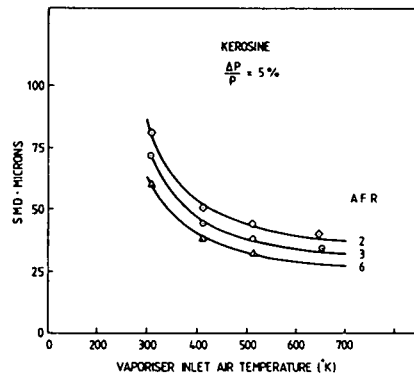


FIG. 8. EFFECT OF VAPORISER INLET AIR TEMPERATURE

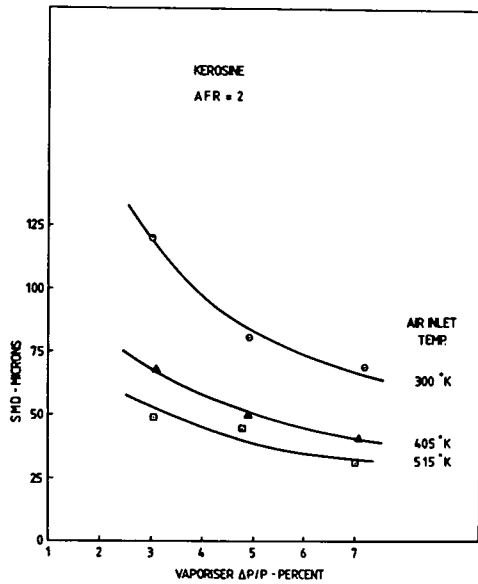


FIG. 6. EFFECT OF VAPORISER PRESSURE DROP

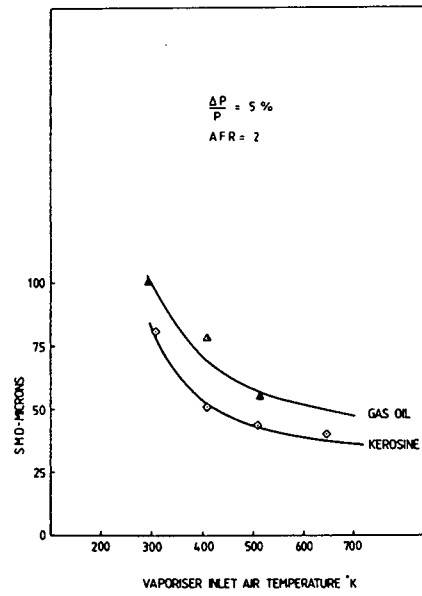


FIG. 9. EFFECT OF FUEL QUALITY

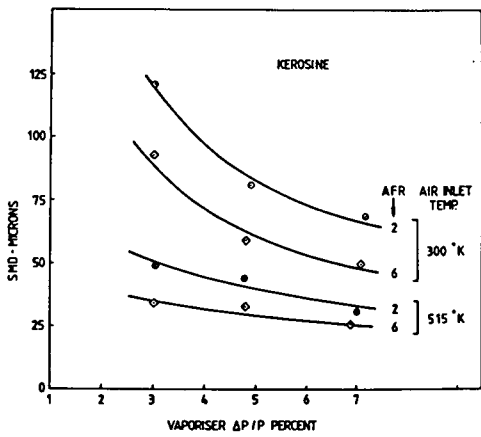


FIG. 7. EFFECT OF VAPORISER PRESSURE DROP

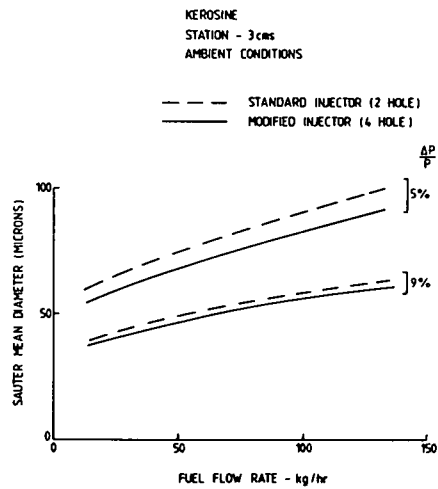


FIG. 10. COMPARATIVE MEAN DROPSIZE PERFORMANCE OF STANDARD AND MODIFIED INJECTORS

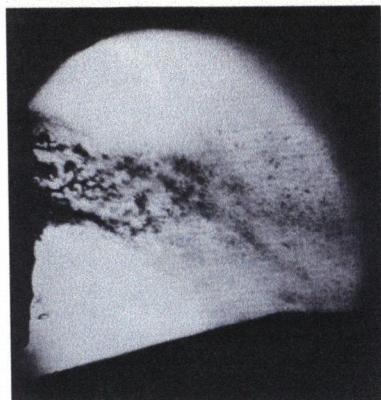
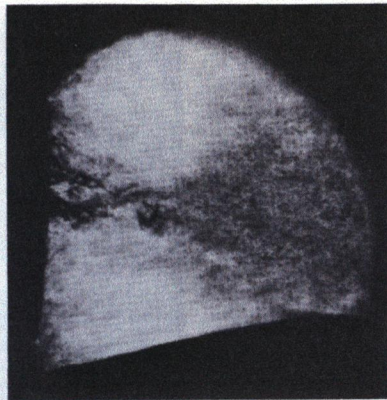
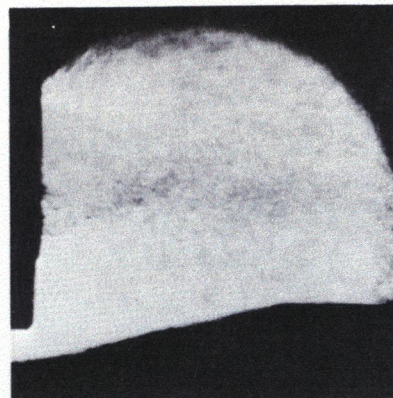
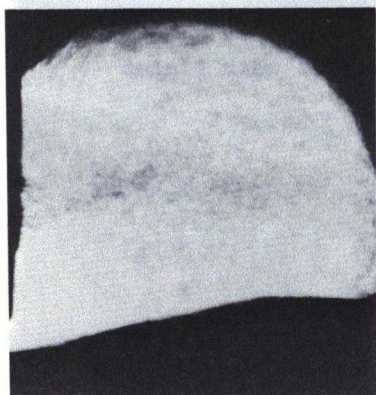
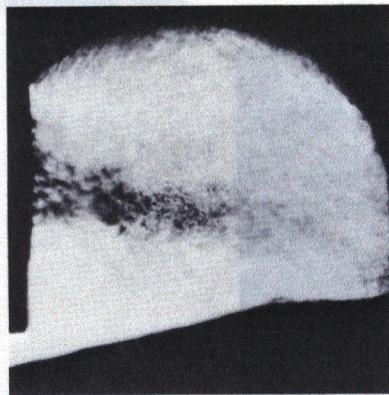
(a) $T_{\text{fuel}} = 300^{\circ}\text{K}$, (NC)(b) $T_{\text{fuel}} = 300^{\circ}\text{K}$, (C)(c) $T_{\text{fuel}} = 423^{\circ}\text{K}$, (C)

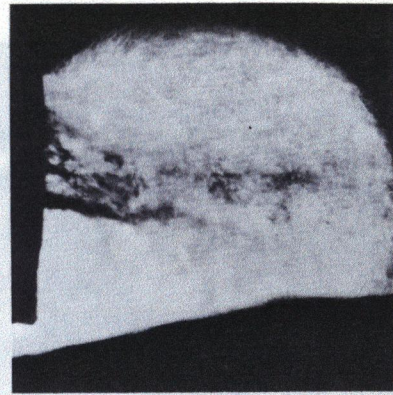
Plate 1 Combusting (C) Versus Non-Combusting (NC) at 380 kPa;
Effect of T_{fuel}



(a) AFR = 6:1



(b) AFR = 5:1



(c) AFR = 4:1

Plate 2 Combustion at 380 kPa - Effect of AFR

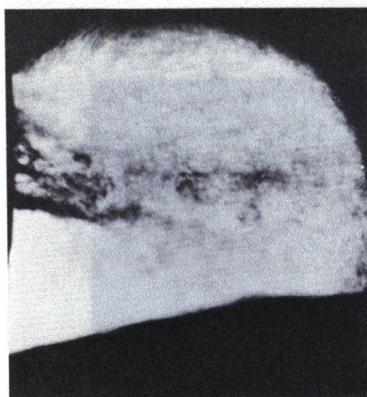
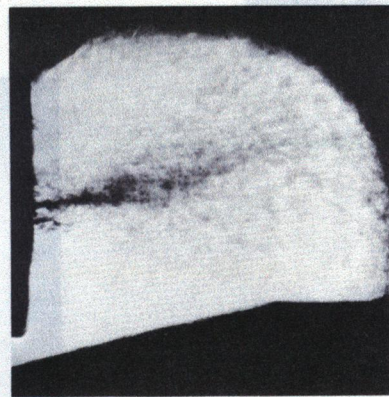
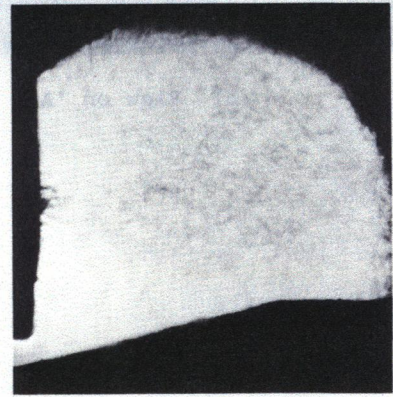
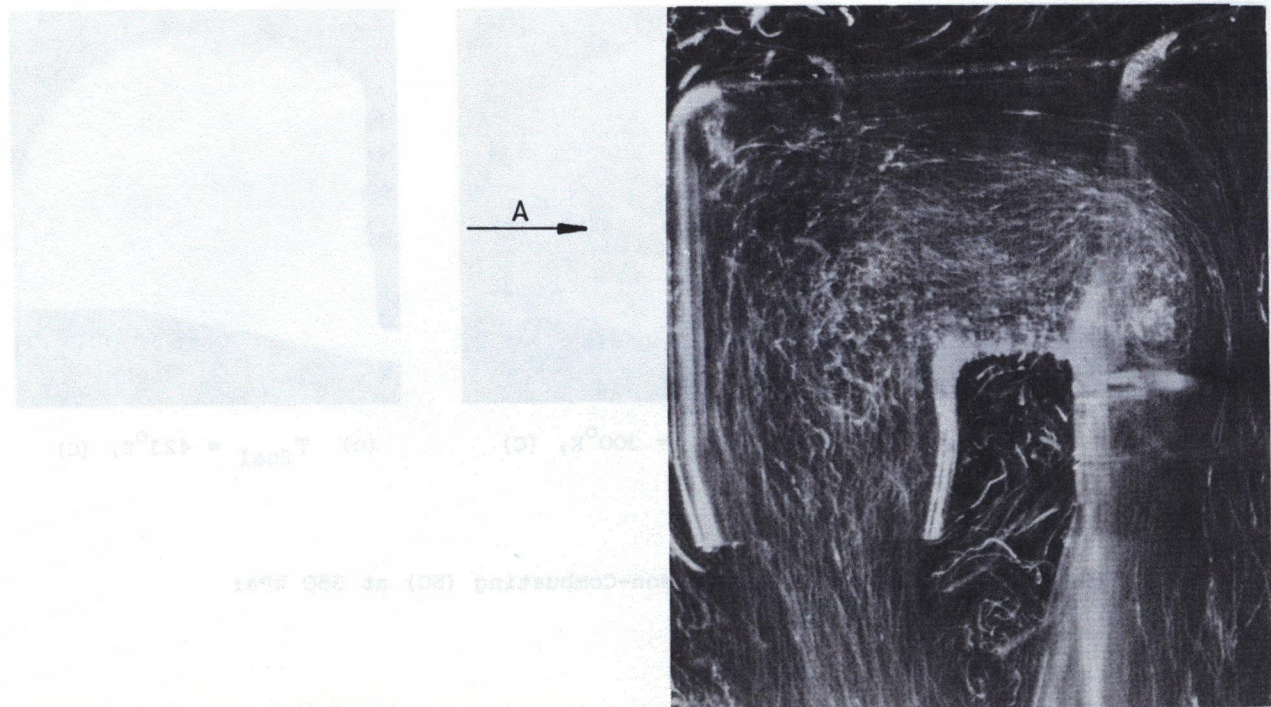
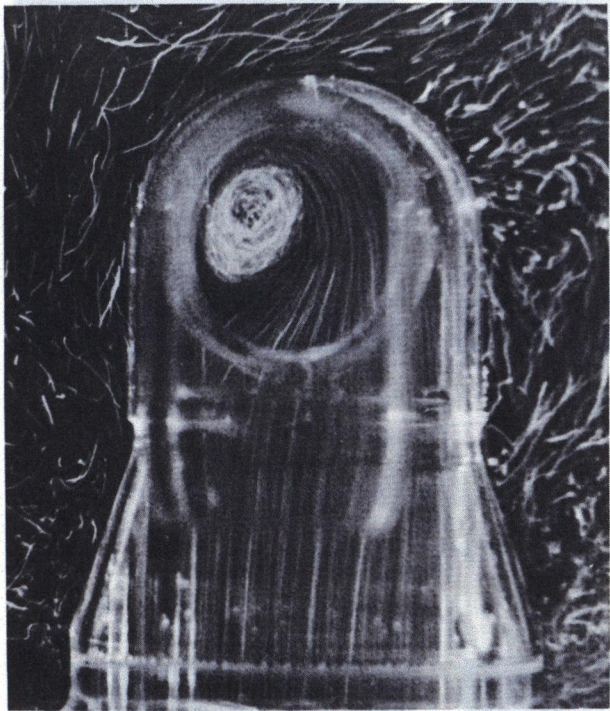
(a) $T_3 = 453^{\circ}\text{K}$ (b) $T_3 = 523^{\circ}\text{K}$ (c) $T_3 = 573^{\circ}\text{K}$

Plate 3 Combustion at 380 kPa - Effect of T_3



(a) Effect of weir plates



(b) View on 'A'

Plate 4 Vaporiser Internal Flows

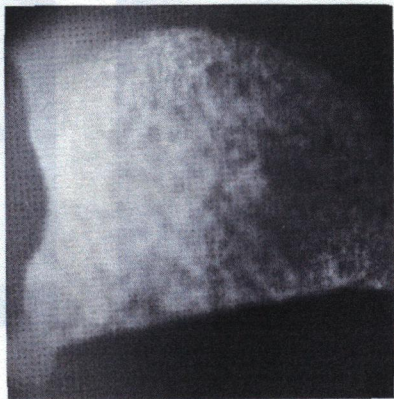
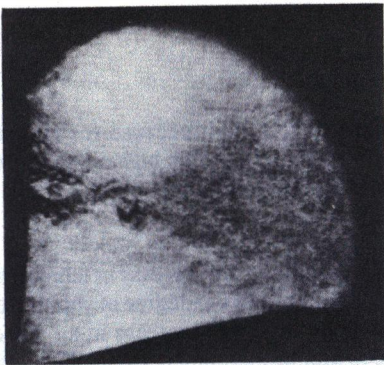
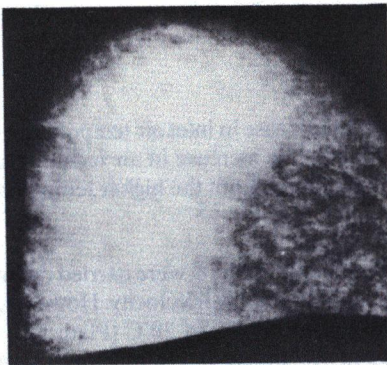


Plate 5 Combustion at 1300 kPa

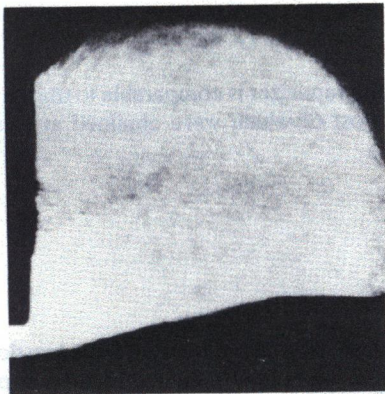


(a) Two-Jet Injector



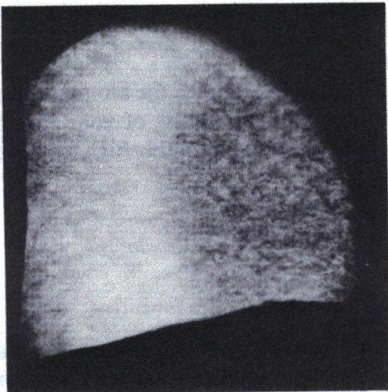
(b) Four-Jet Injector

Plate 6 Combustion at 380 kPa - Effect of Injector Geometry



AVTUR

Condition A

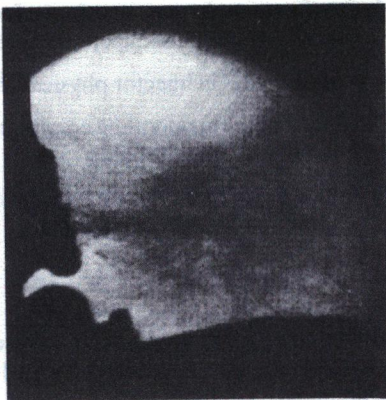


Condition B



DIESEL

Condition A



Condition B

Plate 7 Combustion at 380 kPa - Effect of Fuel Quality

DISCUSSION

A.H.Lefebvre, US

You state that increase in inlet air temperature has a beneficial effect on atomization. Surely this is because, for a constant value of $\Delta P_a/P_a$, an increase in air temperature raises the velocity through the vaporizer. It is this higher velocity that enhances atomization, not the higher temperature which, in fact, has an adverse effect on atomization.

Author's Reply

The tests reported in Plate 3 were carried out at a constant $\Delta P_a/P_a$ and this indeed meant that an increase in temperature resulted in an increase in air velocity. However, the magnitude of the improvement in atomization/degree of vaporization due to a temperature rise of 70°C (Plate 3(b) vs 3(a)) cannot simply be explained by the small increase in air velocity (calculated to be 7 percent). The improved spray quality is, therefore, clearly due to intimate contact between the fuel and the hot air within the vaporizer.

Question

You quote 5 percent as being typical of the pressure drop across a vaporizer. If this is true it represents a basic drawback to the vaporizer system in comparison to the airblast atomizer which functions very satisfactorily with pressure drops of half this value.

Author's Reply

Combustor design is based upon wall pressure drop rather than injector pressure drop. For a given wall loss the pressure drop across the vaporizer is no greater than that across a typical airblast atomizer. The value of five percent quoted in the text arises because the feed to the vaporizer does not incur any diffuser loss. In reverse flow combustors where this is obviously not the case, the vaporizer operates very satisfactorily at pressure drops of less than half this value. In general, though, such comparisons can only be meaningful if performed for the same application/duty.

Question

Your conclusion that the atomizing performance of the vaporizer is comparable to that of an airblast atomizer is difficult to justify on the basis of your experimental data most of which were obtained at values of $\Delta P_a/P_a$ that would be considered unacceptably high for an airblast/nozzle.

Author's Reply

See the reply above.

Question

Have you attempted experiments or calculations to assess the relative merits of these two devices at comparable operating conditions? Fuel vaporization may have much to commend it, but the design features employed to achieve vaporization (random impingement of fuel drops on tube walls, inbuilt pressure losses in bends, etc.) must merely impair performance when the "vaporizer" is operating in an atomizing mode.

Author's Reply

Fuel vaporization, which is clearly high, obviously has much to commend it. Furthermore, the results indicate that the design features do not impair performance in the atomizing mode. However, assessment of relative merits of the vaporizing and airblast injectors under comparable conditions is hampered by

- i) differences in injector physical scales
- ii) differences in operating conditions — for example lack of satisfactory data regarding the effect of air temperature on airblast atomized sprays
- iii) lack of reliable and somewhat universal dropsize correlation — those developed thus far being specific to a given airblast atomizer geometry etc.

G.Grienche, FR

Firstly, I thank you very much for these very interesting experimental results on vaporizers; there are very few. Have you tried to calculate some aspects of fuel droplet motion and evaporation inside the vaporizer and to compare them with experimental results?

Author's Reply

Degrees of vaporization at the outlet have been calculated for two different vaporizer designs and results agree very well with experimental observations. Such calculations, inevitably, have to take into account the heat transfer to fuel as it flows through the vaporizer tubes.

Question

How did you handle the beam steering problem, due to density gradients, in determining the mean diameter?

Author's Reply

The problem of beam steering was tackled by recording the background light signal levels at each of the working air temperatures without liquid fuel injection. Experimental runs featuring fuel injection used these background light levels as the reference — hence effectively countering the beam steering problem.

C.Sanchez Tarifa Sener, SP

In military engines, operational conditions in the combustion chambers will often have gas pressure higher than the critical pressure of the fuel. I would appreciate your view on the possible influence of this effect on the performance of your vaporizing injector.

Author's Reply

Vaporizing combustors do indeed experience pressures well above the critical pressure of the fuel, but in service operation at such conditions need not and has not compromised the integrity/performance of the vaporizer. As at all conditions the fueling level must be sufficient to ensure mechanical integrity of the device. With regard to fuel preparation the effect will be minimal.

H.Pfost, GE

There was little difference in combustion efficiency comparing kerosine with diesel. Any measurements of NO_x emission with respect to the grade of fuel?

Author's Reply

NO_x emissions were measured in the series of engine tests referred to in the text. No increase was observed in tests with the gas oil.

Effect of Injector Geometry upon The Performance of a Plain-Jet Airblast Atomizer

H. J. Pindolia and A. K. Jasuja

School of Mechanical Engineering,
Cranfield Institute of Technology,
Cranfield, Bedford, England

ABSTRACT

This paper presents the results of a study into the effect that liquid orifice orientation has on the structure of the spray emanating from a plain-jet airblast atomizer featuring the injection of multiple liquid jets into a swirling airstream.

Tests were conducted on water at near atmospheric pressure and temperature. Drop sizes were ascertained by using a well-established laser light scattering technique. Variation in drop sizes along and across the spray axis was also examined for a range of operating conditions. The results reveal that the angular orientation of the injection orifice has a considerable influence on the drop size performance of the atomizer studied. This offers the prospect of improved spray performance vis-a-vis design optimization. The structure of the airblast atomized spray was found to be far from uniform, thus highlighting the inadequacy of single point characterisation of fuel injector performance.

INTRODUCTION

The attainment of satisfactory performance from gas turbine combustors over the entire range of operating conditions is generally known to be strongly related to the quality of fuel preparation. In particular the influence of atomization and vaporization performance on such combustion characteristics as ignition (both at sea level and high altitudes), efficiency, flame stability, pollutant emission levels etc. is well established.

The superior performance of the airblast atomizer over the pressure jet type has led to its widespread adoption in the modern high pressure ratio industrial as well as the aero gas turbine. The advantages of airblast atomizers have been discussed in some detail by Lefebvre [1]. The two main types of airblast atomizers in current usage are the so called pre-filming and the plain-jet type. Jasuja [2] has discussed the different configurations along with their merits and shortcomings.

The majority of previous airblast atomization work has been carried out on the pre-filming variety. The principal feature of such an

atomizer is the attempt to generate a thin, continuous, annular liquid sheet of low velocity and to expose this sheet to high velocity airstreams on both sides. This 'sandwiching' action is designed to promote not only high rates of shear through intimate contact between fuel and air but also a spray that is airborne in character. This atomizer configuration has been subjected to on-going research for over two decades now and can be considered to be at a relatively advanced stage of development.

A drawback of the pre-filming configuration, however, is the need to provide for two separate air flow passages within the atomizer body and this not only complicates the design but also makes it more expensive. Because of this the plain-jet type of airblast atomizer, the subject of this and other recent Cranfield studies, is sometimes preferred. In contrast to being pre-filmed into a thin sheet, the fuel is discharged in the plain-jet design in the form of one or more discrete jets into a high velocity single swirling airstream. These fuel jets undergo in-flight disintegration. The extent of atomization is a function of the quality of interaction between the air and liquid and this in turn is dependent on the geometric variables of the liquid injection orifice and the air swirler. The current evidence seems to suggest that the plain-jet configuration offers a system that is comparable in drop size performance to the pre-filming type and yet is simpler and cheaper [2].

The object of this paper is to extend the state of knowledge regarding the design and operational aspects of plain-jet airblast atomization. In particular it deals with the effect of liquid injection orifice orientation upon spray performance. The optimization of plain-jet airblast atomizer geometry has been largely overlooked in the earlier studies. The work reported here is an attempt to remedy this and is a part of an on-going programme of research into plain-jet airblast atomization at the laboratories of the Cranfield School of Mechanical Engineering. Further details of this study can be found in reference 3.

EXPERIMENTAL PROGRAMME

As stated before, the major variable selected for this study was the angular orientation of the

Contributed by the Fuel Society of Japan for presentation at the 4th International Conference on Liquid Atomization and Spray Systems held in Sendai, Japan from August 22nd to 24th, 1988.

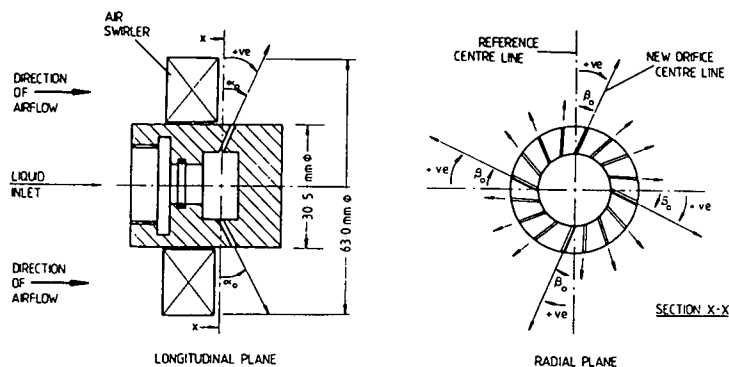


FIGURE 1 ATOMIZER GEOMETRIC VARIABLES

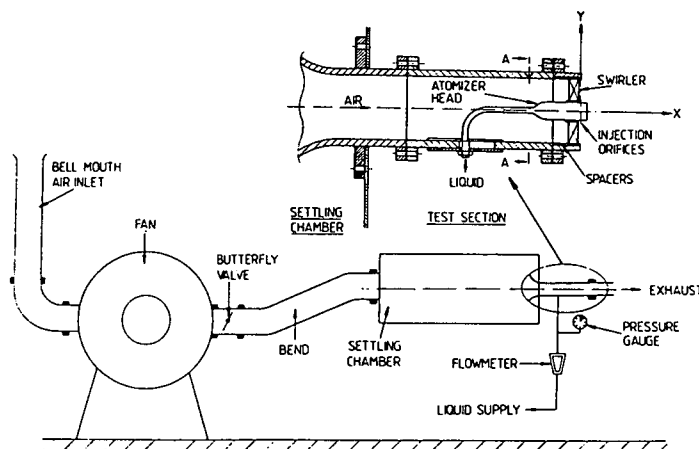


FIG 2. SCHEMATIC DIAGRAM OF TEST RIG.

liquid injection orifice. This was varied in two directions - longitudinal and radial as depicted in figure 1. Limited amount of experimentation featured the effect of air-to-liquid mass ratio and the airstream velocity.

The approximate range of conditions actually covered in the experiments were:-

Airstream velocity

(at inlet to swirler) = 50-130 m/s

Airstream density = corresponding to normal pressure and temperature conditions.

Air-to-liquid mass ratio, ALR = 1-10

Swirler air pressure drop = 2-10 percent

Dropsizing measuring station location in longitudinal direction, ie, X = 50, 100 & 150 mm from the swirler face.

Injection orifice diameter, d = 1.3 mm

Injection orifice l/d ratio = 4

Number of injection orifices = 16

Angular orientation of injection orifices:

- (i) Longitudinal plane $\alpha_0 = -30^\circ$ to $+45^\circ$
- (ii) Radial plane $\beta_0 = 0^\circ$ to 60°

Swirler Vane Outlet angle $\gamma = 30^\circ$

The atomizer used in this study was of a design generally similar to that used by Hussein [4] and Shaw [5] with the exception of the outlet angle of the curved vane air swirler. Both these earlier studies [4,5] featured a 65° outlet angle curved vane swirler. Turning the air through such a large angle resulted in a relatively high air pressure drop (circa 16 percent for a modest outlet axial air velocity of 70 m/s) - thus rendering such a design impractical for usage in the gas turbine engine. The use of a 30° outlet angle curved vane air swirler in this study was an attempt to achieve an atomizer design that was not only practical but also effective in terms of spray performance. Further evidence regarding the benefits of incorporating air swirlers into airblast atomizers is provided by a recent study reported by Aigner and Wittig [6]. A large number of inter-changeable atomizer heads, designed to enable the angular orientation of the liquid jet array to be varied independently in the longitudinal as well as radial directions, were employed in this experimental programme. It should be stressed here that the angular variations were carried out singularly, ie, either in the longitudinal or radial direction and not simultaneously in the longitudinal and radial directions.

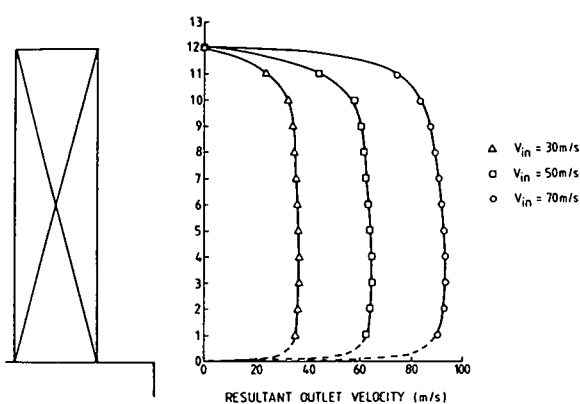


FIG. 3. AIR SWIRLER EXIT VELOCITY PROFILES

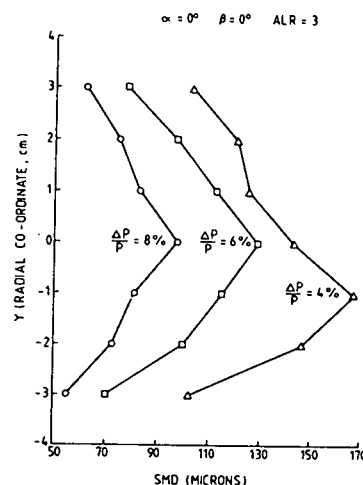


FIG. 4. VARIATION OF SMD ACROSS THE SPRAY
X = 5 cm

EXPERIMENTAL DETAILS

The test facility utilised in this investigation is shown schematically in figure 2. Air at near normal atmospheric pressure and temperature was drawn into a settling chamber that was connected to a plexi glass circular test section through a bell mouth intake. The mass flow of air was ascertained in accordance with BS1042. The air velocity at inlet to the swirler was measured using a static and total pressure probe while the outlet velocity was obtained by using a Cobra probe. This three tube combination probe enabled the resultant velocity profile at the air swirler exit to be measured by balancing the outer two tubes and recording the total pressure in the middle tube.

As the effect of liquid properties on spray quality has been studied extensively by Jasuja [7] water ($\eta = 0.001$, $\sigma = 0.735$, $\rho = 1000$) was the only spray medium used in this investigation. It was supplied to the atomizer by a multistage pump through a bank of calibrated precision flow meters.

The spray Sauter Mean Diameters were measured using the well-established, non-intrusive, laser light-diffraction technique. The optical technique is based upon the principles of forward diffractive scattering of a parallel, monochromatic beam of light as it passes through the test spray thus yielding SMD values for the entire droplet population intercepted by the collimated light beam along its path. This technique has been used extensively for the earlier airblast atomization research (Refs. 4,5,7). Generally speaking, the technique has been observed to yield satisfactory mean drop-size results down to about 20 microns for a wide variety of fuel injector types as well as their operating conditions. To ensure the reliability of the experimental results, the optical bench was calibrated and checked for accuracy in operation by using a pressure jet type of Delavan injector of a known drop-size performance. The complete optical bench was mounted on a platform that could be traversed both along and across the spray axis, i.e. in X and Y directions as shown in Fig 2.

RESULTS

Before outlining the dropsizes results it is perhaps worth examining the air swirler outlet velocity profile data, in brief, because of its obvious influence upon atomization performance. Figure 3 features outlet velocity profile data for 30, 50 and 70 m/s air velocities at swirler inlet. As is evident from this figure, the velocity profiles are mostly flat except near the edges where the velocity falls off because of the boundary layer influence. Outlet velocity profiles appear to be unaffected in character by the level of air velocity at the swirler inlet. Clearly information of this kind is useful when attempting to optimize the atomizer geometry - for example it may enable the liquid injection orifice to be oriented in a manner that encourages maximum physical contact between the liquid and air.

The bulk of the spray data available at present takes the form of drop size measurements along a narrow, usually few millimetre diameter, collimated line of sight through the centre of the spray envelope. The inadequacy of such data is being increasingly recognised from fundamental as well as combustion hardware design/development viewpoints. For example knowledge of spatial distribution of dropsizes at near atmospheric air pressure and temperature level would be helpful not only in diagnosing but also minimising ignition/start-up problems experienced by gas turbine engines operating at sea level. A start has been made in this investigation at identifying the degree of maldistribution prevalent in plain-jet airblast atomized sprays in an attempt to somewhat ameliorate this unsatisfactory state of affairs. Results of dropsizes traverses at 4, 6 and 8 percent atomizer air pressure drop levels for the 5 and 10 centimetre measuring station locations (when measured from the air swirler outlet face along X axis - see Fig 2) are depicted in figures 4 and 5. The injection orifice is oriented to deliver transverse jets of liquids (i.e. $\alpha = \beta = 0^\circ$) for these traverses at a typical air-to-liquid ratio of 3. Furthermore, the usual convention has been adopted with regard to traversing across the spray, i.e. along the Y axis

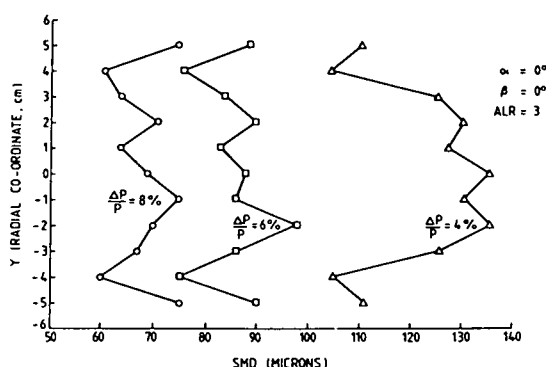


FIG. 5. VARIATION OF SMD ACROSS THE SPRAY
X = 10 cm

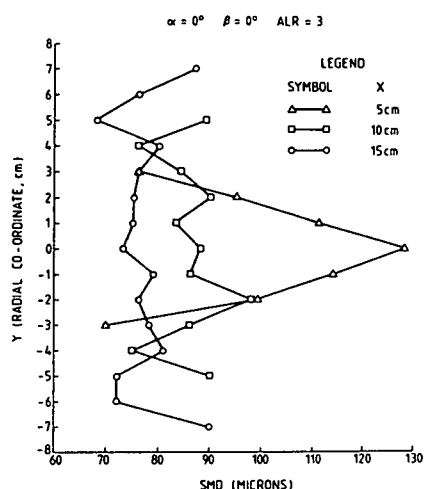


FIG. 6. VARIATION OF SMD ACROSS THE SPRAY AT $\frac{\Delta P}{P} = 6\%$

as shown in Fig 2. Positive values of measurement location indicate movement in the radially upward direction or characterisation of the top half of the spray while negative values relate to the measurements in the bottom half of the spray.

It is clear from these figures that the structure of the atomized spray is far from uniform. The mean dropsizes can be observed, in figure 4 for example, to vary considerably across the spray cross-section thus highlighting the inadequacy of single point characterisation of fuel injector performance. For the 5 centimetre measuring station location (i.e. X = 5 cm) the drop size values at or near the spray centre are significantly higher than those at other positions. Furthermore the beneficial influence upon atomization quality of an increase in atomizer air pressure drop is clearly evident in figures 4 and 5.

Figure 6 illustrates the effect of varying the location of dropsizes measuring station in the longitudinal direction (i.e. in X direction) upon spray non-uniformity for a typical atomizer air pressure drop of 6 percent. Maximum degree of dropsizes non-uniformity is observed at the

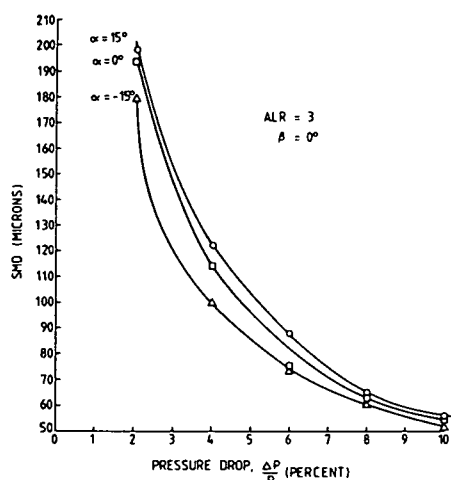


FIG. 7. VARIATION OF SMD WITH PRESSURE DROP

measuring station located nearest to the atomizer and further downstream of this position continuing disintegration of droplets helps to reduce this level of maldistribution. Also evident from this figure is the widening spatial liquid distribution envelope with downstream distance since measurements of dropsizes were carried out to the extremities of the spray at all the three locations. This widening of the spray envelope is due simply to its conical character.

Engineers are continually required to design gas turbine combustors/injectors to operate satisfactorily with a minimum of air pressure drop. As a consequence the aerodynamics of the atomizer air flow features need to be carefully optimised in order to obtain the most effective pressure drop-air velocity conversion. Figure 7 illustrates the effect that atomizer air pressure drop has upon Spray Sauter Mean Diameter for a range of injection orifice angular orientations. Clearly the higher the available air pressure drop the superior the spray quality for the entire range of injection orifice orientations studied. There is, however, a somewhat sharper deterioration in spray performance as the pressure drop falls off below about 4 percent. This is nothing new since airblast atomizers are known to exhibit a somewhat poorer drop size characteristics at lower airstream velocities.

Air-to-liquid ratio is another important variable influencing the spray performance. Inadequate amount of air would be expected to result in failure to overcome the viscous/surface tension forces resisting liquid break up where as an excess of air may lead to some of the air not actually contributing to liquid disintegration. The sizing of the air passages is clearly a function of the atomizer air mass flow. Figure 8 depicts the variation in spray SMD with air-to-liquid ratio for a typical air pressure drop of 4 percent. The curve relating to the injection orifice orientation in radial plane of 30° (i.e. β = 30°) with 30° swirler vane outlet angle (i.e. γ = 30) shows a trend that contradicts expectations based on earlier airblast atomization work [2,5]. A typical example of the expected

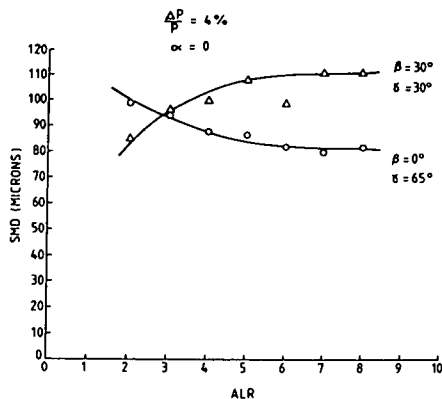


FIG. 8. VARIATION OF SMD WITH ALR

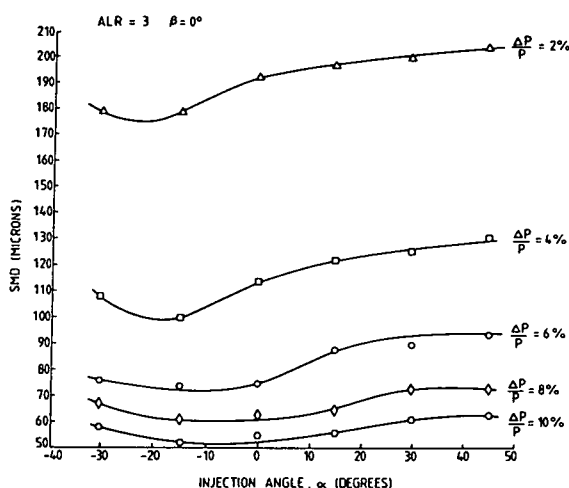


FIG. 9. VARIATION OF SMD WITH LONGITUDINAL INJECTION ANGLE

trend is illustrated by the curve featuring $\alpha = \beta = 0^\circ$ and $\gamma = 65^\circ$. This peculiar trend, i.e. an increase in SMD with an increase in ALR, is considered to be due to the basically flatter velocity profile at the outlet of the 30° air swirler relative to the 65° swirler. The liquid jets are impacted by a relatively high velocity airstream almost as soon as they emerge from the injection orifice. At higher ALR values (and hence at higher airstream momenta) the liquid jets were bent to such an extent that they were running along the atomizer hub body as liquid streams. This resulted in the liquid being discharged in the form of rather coarse streaks from the solid, front face of the atomizer hub. Adjoining this solid face is a recirculatory region of low air pressure/velocity and consequently liquid streaks would be expected to result in rather large droplets to begin with. Their subsequent disintegration would depend upon the intensity of interaction with the surrounding air. It should be recalled here that the outlet angle of the curved vane air swirler was reduced from 65° to 30° for this study in order to achieve a more practical air swirler design from pressure drop -

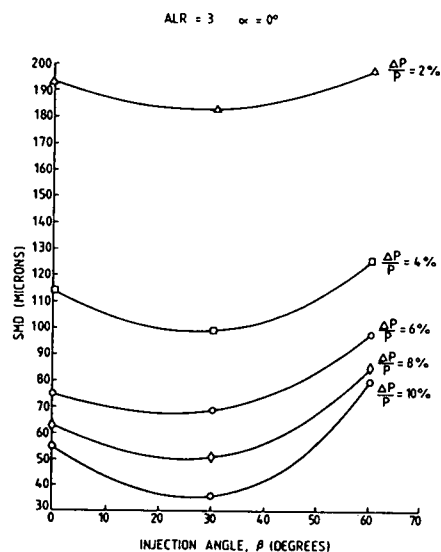


FIG. 10. VARIATION OF SMD WITH RADIAL INJECTION ANGLE

velocity interchange considerations. Clearly further improvements in atomizer/swirler geometry are required to alleviate this streaking problem. As this is an on-going programme, it is hoped to pursue these geometry related improvements in the near future and at the same time quantitative spatial distribution of injected liquid would also be measured. Quantitative liquid distribution measurements for a non-optimal configuration were considered somewhat unnecessary in the interests of minimising expenditure of time, effort and money.

The effect upon SMD of varying the angular orientation of the injection orifice in longitudinal and radial planes is illustrated in figures 9 and 10 respectively. As is evident from these figures variations in longitudinal and radial injection angles, i.e. α and β respectively, can have a noticeable impact upon the spray mean droplet size for the entire range of air pressure drops covered. A consequence of a change in injection angle α, β is to alter the relative velocity between the liquid and air streams. Increase in relative velocity will lead to a more intense interaction and consequently higher rate of deformation of jets as well as drops. Conversely a lowering of relative velocity will have an adverse influence on the disintegration process.

CONCLUSIONS

The main conclusions that can be drawn from this work are as follows:-

- 1) The structure of the airblast atomized spray studied is far from uniform as revealed by droplet size traverses. The variation in droplet sizes across the spray cross-section can be quite considerable thus highlighting the inadequacy of single point characterisation of fuel injector performance.

- 2) The angular orientation of the liquid jet in the radial as well as the longitudinal directions can have a significant impact upon spray performance of a plain-jet airblast atomizer.
- 3) Further work is needed on the plain-jet airblast atomizer to eliminate the problem of liquid streaks as well as to assess the extent of performance benefits to be realised by orienting the liquid jets in a compound direction (ie. combined radial and longitudinal angle).

7) Jasuja, A.K. "Plain-Jet Airblast Atomization of Alternative Liquid Petroleum Fuels Under High Ambient Air Pressure Conditions". ASME Paper, No 82-GT-32.

NOMENCLATURE

ALR	- Air to liquid mass ratio
d	- diameter, mm
m	- Mass flow, kg/s
p	- Pressure, atmospheres
$\Delta P/p$	- Atomizer air pressure drop, %
SMD	- Sauter Mean Diameter, micron or m
T	- Temperature, °K
V	- Velocity, m/s
X	- Longitudinal coordinate, ie along the spray, see Fig 2
Y	- Radial coordinate, ie across the spray, see Fig 2
α, β	- Liquid injection angles
γ	- Swirler vane outlet angle
η	- Absolute viscosity, Ns/m ²
ρ	- Density, Kg/m ³
σ	- Surface tension, N/m

Subscripts

a	- air
in	- inlet
j	- jet (liquid)
l	- liquid
o	- orifice (injection)

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the kind help, interest and support of all the individuals who have made this paper possible.

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VISUALIZATION OF AIRBLAST ATOMIZED SPRAY STRUCTURE UNDER VARYING AIR PRESSURE CONDITIONS

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ABSTRACT

This paper reports the findings of a non-burning spray visualization study conducted on state-of-the-art gas turbine fuel injector - combustor head assembly hardware under varying air pressure conditions. Four different airblast injectors of the pre-filming type were tested on aviation kerosine from simulated ground idle to simulated take-off condition. The optical diagnostics employed comprised a combination of short-duration, high-intensity, spark photography together with high speed cine and video imaging. The sprays studied are found to exhibit non-uniform structure in respect of droplet concentration and trajectory. Furthermore, airblast injector design and operating conditions are observed to have a significant effect upon spray droplet placement and number density within the combustor primary zone environment. Systematic analysis of the experimental data yields a useful correlation between spray width and key injector design - operating variables. This improved understanding identifies more clearly the combustion-emissions as well as the dense spray characterisation challenges that lie ahead.

NOMENCLATURE

A_{Datum}	=	Datum airflow area - injector	
A_{eff}	=	Effective airflow area	-
AFR	=	Atomizer air to fuel mass ratio	
ϕ_c	=	Characteristic diameter	-
ϕ_{PF}	=	Pre-filming diameter	
θ	=	Air swirl angle - average.	

1. INTRODUCTION

Unrelenting pressures for improvements in fuel economy, flexibility and performance together with the current concern for the environment make spray combustion a topic of paramount importance for the modern gas turbine engine. Satisfactory fuel-air mixture preparation is widely accepted as being crucial in their realisation. This is

necessary not only during the sea level ignition and take-off phases of the combustor operation but also during intermediate-power cruise and climb phases. In general, atomization is accomplished easily by creating a high relative velocity between the fuel and air and it is usual to aim for good spray performance throughout the operational range of the combustion chamber. However, the droplets in a spray are inhomogeneously distributed in space with wide variations in their size, velocity, number density and ballistics. Experimental research to date, has largely been confined to dilute and simple sprays operating in easily probed laboratory conditions. Consequently the formation of a spray of droplets from full scale industrial nozzles as well as its subsequent interaction with the high-density, aero-thermodynamic environment of the practical combustion zone is far from adequately understood. This lack of information regarding the complex and important near-field, bulk liquid behaviour and droplet physical processes within a dense spray is hindering the current computational efforts relating to the development of a satisfactory dense spray modelling capability.

Airblast atomizers have been used widely in the modern, high-pressure ratio aero gas turbine because of the particular need for cleaner combustion with minimal of soot/smoke and other pollutant emissions. This is due to the well mixed and finer character of airblast spray. Thus far, its placement in the primary zone has been believed to be dictated mainly by the prevailing combustor aerodynamics - making it, apparently, almost insensitive to fuel flow variations. Despite widespread adoption, the level of knowledge concerning the detailed structure of airblast spray and the nature of its variation with design-operational variables is largely unsatisfactory. For example, the effect of air density upon the size and velocity of droplets in a spray has been reported in a rather restricted manner in references 1 and 2. Visualization of spray/droplet behaviour has fared even worse - such studies having focussed attention either on simple research atomizer geometries or practical geometries operating in atmospheric conditions. This paper reports the findings of a visualization study directed at extending the information available regarding the near-field trajectories and spatial distribution of spray droplets

emerging from airblast atomizers under varying air pressure conditions. In addition, the combustor head features as well as the airblast atomizers used in this study were fully representative of the current industry practice - as indeed were the operating pressures and fuel flows.

2. EXPERIMENTAL PROGRAMME

All the airblast fuel injectors used in this research study belonged to the generic family of atomizers identified in the spray literature as the pre-filming type - see figure 1 for outline details. In such atomizer designs liquid is first spread into a, supposedly, thin, uniform and continuous annular sheet on a pre-filming surface before exposure to the shearing action of high-velocity, swirled, inner as well as outer airstreams. Sandwiching of the liquid sheet upon leaving the pre-filming surface is designed not only to promote intimate physical contact between the two fluid streams but also to ensure that the resulting droplet cloud remains largely airborne. All the injectors were typical of the current gas turbine industry practice and differed from each other in respect of air flow features - effective area, swirl vane design/angle etc.

The experimental set up used in this investigation is illustrated in figure 2. At the outset it was considered that the experiments should be conducted under as realistic an environment as was practical. As combustor head air swirler and other major dome air flow features can have a profound effect on the formation and transport of spray droplets it was desirable to incorporate them into the test section. Consequently each injector, dome swirler and head assembly was mounted, individually, into an airbox-plenum chamber that was connected to a high pressure air supply system. The airbox assembly was in turn mounted inside the high pressure fuel spray rig. A throttle at the pressure drum outlet together with a control valve on the airbox inlet enabled the establishment of correct test conditions. The vessel featured optical access at three positions, two along a horizontal diameter with the third one at top location, for monitoring the structure of the atomized spray over a range of air pressures, air velocities, fuel flow rates etc. Standard aviation kerosine was the test fuel for the entire study. The air and fuel flow conditions were set using calibrated precision flowmeters and gauges.

Imaging is a popular and convenient optical technique for studying liquid sprays. It enables the mechanism of spray formation to be investigated together with the visualization of the prevailing structures. The actual diagnostics employed herein comprised a combination of high-intensity spark photography together with high speed cine and video imaging. This was considered to provide an optimum combination of higher quality instantaneous images along with the capturing of dynamic and unsteady elements of spray behaviour.

The intensity and duration of the spark emitted by the pulsed light source is of vital importance from the standpoint of spray image quality. The intensity of the pulse requires to be sufficiently high so as to penetrate and visualize the core regions within a dense spray. The duration of the spark needs to be small to "freeze" the fluid motion. A commercially available argon jet flash unit was used in the

study. The pulse duration was about 500 nsec and the triggering was performed by the shutter of a Hasselblad camera.

Mercury vapor illumination with appropriate collimating optics was used for high speed cine and video recordings. A NAC high speed cine camera was used to film the less dense, lower fuel flow sprays at 5000 fps with a 10:1 shutter and at 4000 fps with a 3:1 shutter for the high power, dense sprays. Video images were obtained with a Spin-Physics SP2000 video system at typically 500 fps.

3. RESULTS

3.1 Photographic Data

During the course of this investigation a large number of spray images have been recorded using the high speed cine-video and spark photographic techniques. Due to limitations of space, only a small proportion of the data accumulated is presented in this paper. Arguably this deliberate process of selection could introduce a bias into the interpretation and analysis of the experimental data. However, care has been taken to ensure that the information included herein is a realistic representation of the overall situation.

Plate 1 illustrates the structural change encountered by the kerosine spray emanating from injector 2 as the operating condition is changed from a simulated typical ground idle to a simulated typical take-off. The shift to higher operating power under non-burning conditions can be seen to yield a spray that is increasingly dense in character. The dilute-dense region mix within the non-burning spray seemingly follows the engine operating line. The more dense spray being characterised by fewer voids and consequently lower void fraction. At the highest power the spray is so dense that the structural details of the core are largely inaccessible. However, at the spray boundaries some eddy structures, due to interaction with the prevailing environment, can be observed. The width of the spray upon exit from the injector is almost insensitive to operational changes - perhaps reflecting simply the physical constraint imposed by the fixed design geometry of the nozzle. Further downstream, though, the spray appears to spread out spatially to a greater extent with an increase in operating power.

Shown in plate 2 are the spray images for a given ground idle condition simulation for injectors 1, 2 and 3 respectively in order to illustrate the effect of nozzle design geometry upon spray performance under non-burning conditions. It should be pointed out here that for this experimental data different injectors have been tested with the same combustor dome hardware to ensure that the comparisons are consistent, meaningful and representative. A close examination of the plate 2 data reveals a variation not only in the width of the spray upon exit from the injector but also in the subsequent spray trajectory - cone angle. For a given fuel throughput a more compact efflux at the injector exit will inevitably yield a relatively dense spray to begin with and this, in fact, is borne out by the photograph of injector 1. In addition, the far-field spray plume from this injector continues to exhibit a somewhat denser structure. Clearly the injector design can be seen to have a

profound effect upon spray structure and its spatial distribution in a given combustor primary zone.

3.2 Photographic Data Reduction

Photographs yield a qualitative insight into the global effect that different variables have upon the structure and placement of fuel spray. The usefulness and applicability of such information is somewhat restricted unless it can, somehow, be used to develop quantitative trends. The vast amount of photographic data collected in this study were measured for spray plume width at one pre-filmer diameter from the injector face. Detailed and systematic analysis of the correlation between the foregoing measurements and the test conditions were undertaken and is contained in this section.

Figure 3 is a plot of variation in spray envelope width against fuel flow for a range of injector designs and vessel air pressures. Implicit in the combined injector fuel flow and inlet air pressure - mass flow variation is the movement along the engine operating line: low fuel flow-air pressure corresponding to low power whereas higher fuel flow-air pressures relate to higher power. The width of the spray envelope, at a downstream distance of one pre-filmer diameter, varies noticeably with the combustor primary zone flow conditions in a non-burning environment. The impact of injector design upon spray plume width can be observed to be even more profound.

The data in figure 4 is a cross-plot of that in figure 3 in order to illustrate more precisely the effect that injector air to fuel mass ratio (AFR), has upon the spatial spread of the spray. In airblast atomization the importance of injector AFR to the formation and quality of the fuel spray is well documented^{5,6}. From the optimal droplet size performance standpoint, airblast atomizers are usually designed to operate with an atomizer AFR in the 2 to 5 range. Deficiency of air is claimed to give poor atomization performance while an excess of it is believed to be wasteful as some of the air is physically too remote to effectively participate in the various spray processes. The size of the air passages (and consequently atomizer overall bulk and weight) is clearly dependant upon the amount of air required to be passed through them. The data contained in figures 4 & 5 provides some insight into the hitherto unclear inter-relation between atomizer AFR and spray trajectory/distribution. A reduction in AFR from 11 to around 5 in figure 4 yields an increase in the width of the non-burning spray plume although the extent of this increase varies between injectors. This is perhaps not entirely surprising as the aerodynamics of air passages are unlikely to be identical for the different injectors. Interestingly spray width of injector 4, which was tested independently of the combustor head air flows in contrast to tests on injectors 1, 2 and 3 with head air flows, exhibits the greatest sensitivity to AFR variations (Figure 5). Without additional information it is not possible to identify the precise cause of this greater sensitivity viz different injector designs or different mode of testing etc. It should be mentioned here that the change in AFR was obtained by keeping the level of air flow fixed and varying the fuel mass flow.

In airblast atomization the formation and transport of spray droplets is well known to be a

function of the momentum interchange between the atomizing and the atomized media. The more intense this momentum transfer the finer and more easily transported are the ensuing spray droplets. Consequently it is logical to explore a link between spray distribution and fluid stream momenta. The earlier data has been re-plotted in figures 6 and 7 to illustrate the effect of fuel-to-air momentum ratio upon the width of the spray plume. In general, wider sprays correspond to higher fuel-to-air stream momentum ratios: reflecting simply the relative ease with which fuel stream featuring proportionately higher momentum is able to penetrate the air surrounding it. The efficacy of momentum transfer vis a vis the injector design geometry is also brought out by these figures.

A close examination of figure 6 reveals a discontinuity between high and low AFR data sets for a given injector type ie larger spray width for a lower momentum ratio at an AFR of 11 relative to the narrower spread for a high momentum ratio at an AFR of 4.84. This would seem to imply that the AFR effect on spray width is not fully accounted for by the momentum ratio and consequently needs to be incorporated further into data analysis. The discontinuity of figure 6 has been eliminated in figure 8 by plotting spray width against the product of fuel-air momentum ratio and (AFR)^{1/6}. Variations in injector design geometries can still be seen to yield widely different spray envelope widths. By taking into account the key geometrical features of the various injector designs, the data of figure 8 can be made to converge into a single correlation as depicted in figure 9. It is expected that accuracy and applicability of the correlation developed herein would improve as more experimental data becomes available.

4. CONCLUDING REMARKS

High speed visualization of fuel sprays has been shown to be a useful and highly desirable topic of investigation in order to extend our understanding of gas turbine spray combustion phenomenon in a near industrial environment. Sprays covered in this investigation are found to exhibit an inhomogeneous structure in respect of droplet concentration and ballistics. Furthermore, airblast injector design as well as operating conditions are observed to have a profound effect on spray placement and structure. Visualization, although primarily a qualitative tool, has been demonstrated to be capable of yielding quantitative information concerning spray characteristics.

The non-uniform and variable nature of fuel sprays has implications for the realisation of satisfactory combustion-emissions performance. Unsatisfactory spray evaporation performance coupled with poor fuel vapour - air mixing could affect the flame characteristics with consequences for soot and other pollutant species. Equally, characterization of such sprays using point measurement techniques such as laser-phase Doppler anemometry will require additional care and thought if misleading results are to be avoided.

5. ACKNOWLEDGEMENTS

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Rolls Royce and Cranfield Photographic
Departments.

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FIG 1 TYPICAL AIRBLAST INJECTOR

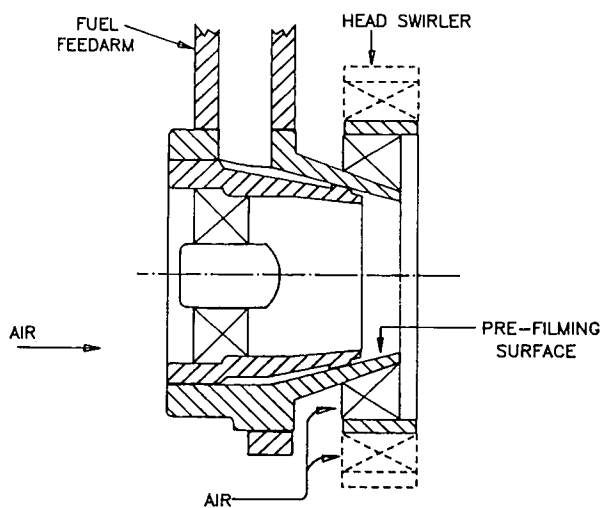


FIG 3 SPRAY WIDTH AGAINST FUEL FLOW

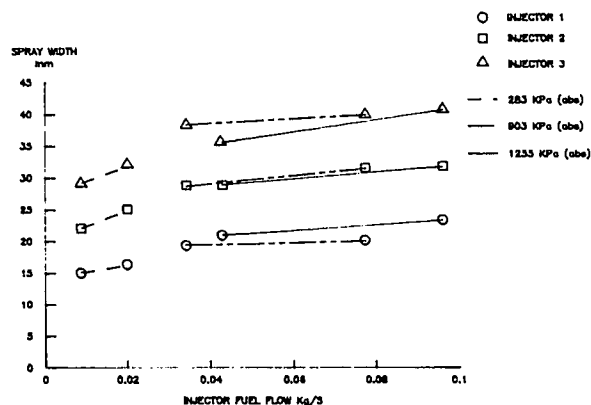


FIG 2 HIGH PRESSURE FUEL SPRAY FACILITY

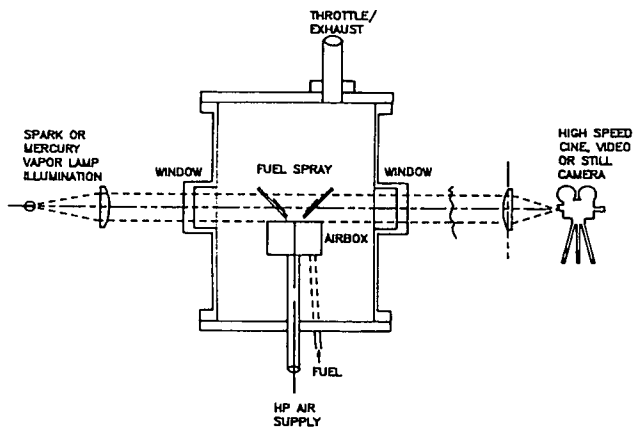


FIG 4 SPRAY WIDTH AGAINST AMBIENT PRESSURE

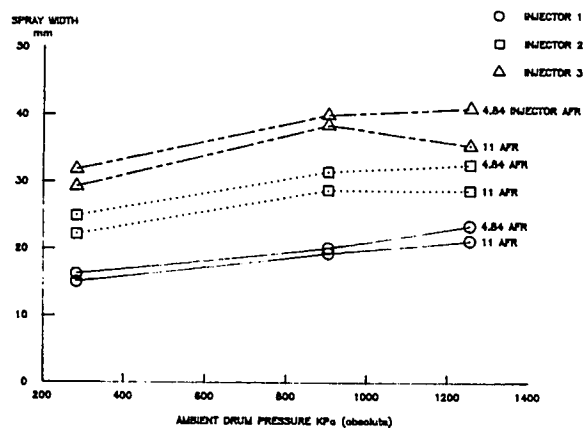


FIG 5 SPRAY WIDTH AGAINST AMBIENT PRESSURE
INJECTOR 4

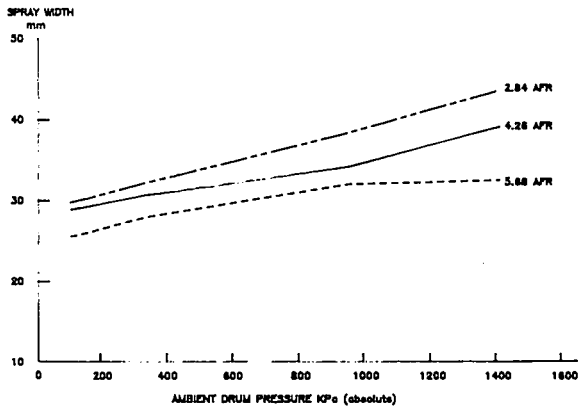


FIG 7 SPRAY WIDTH vs FUEL/AIR MOMENTUM RATIO
INJECTOR 4

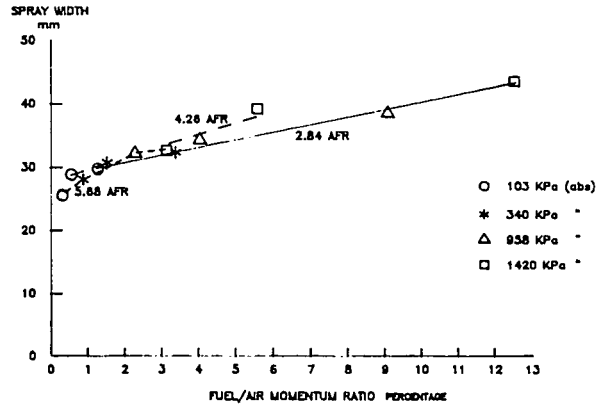


FIG 6 SPRAY WIDTH vs FUEL AIR MOMENTUM RATIO

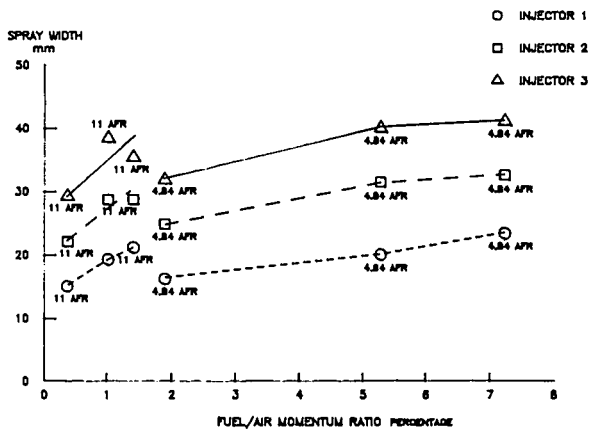


FIG 8 SPRAY WIDTH vs FUEL AIR MOMENTUM RATIO + (AFR)^{1.6}

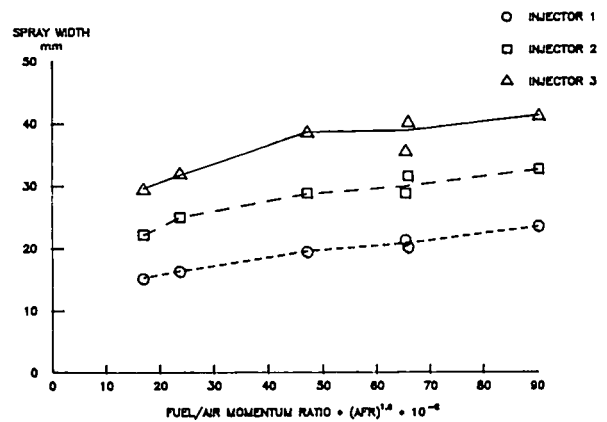
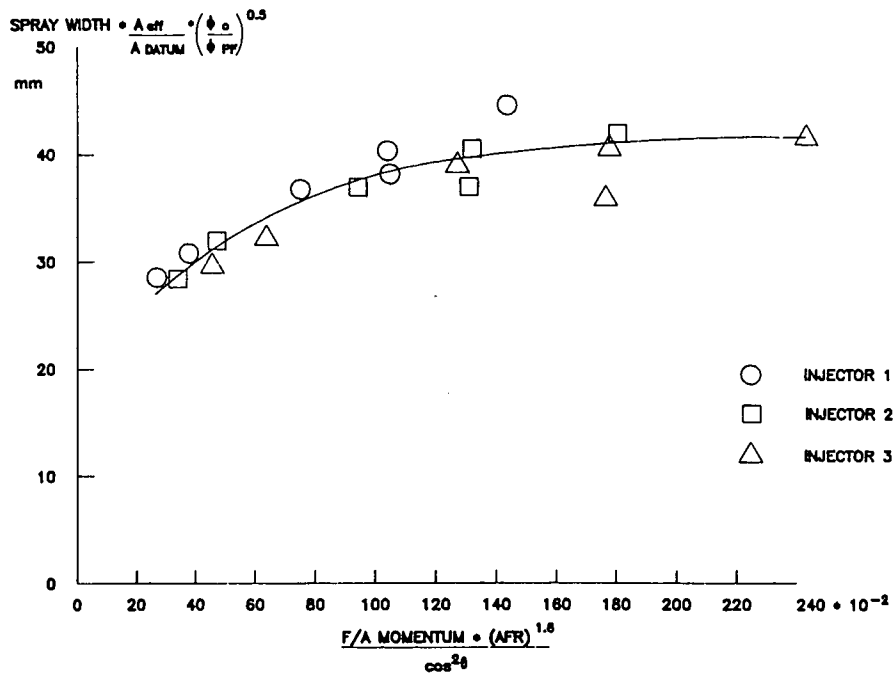
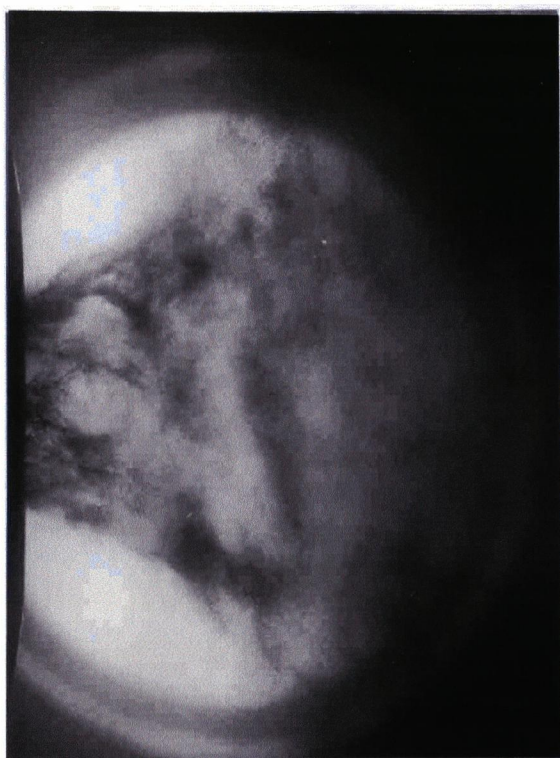


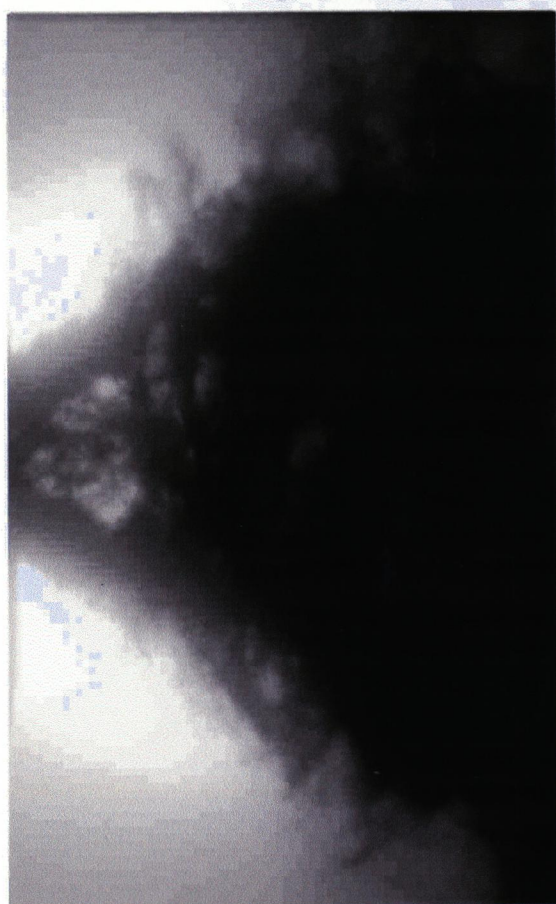
FIG 9

SPRAY WIDTH CORRELATION





← SIMULATED GI



↑
SIMULATED TAKE-OFF

PLATE 1



← INJECTOR 1



↑
INJECTOR 2



← INJECTOR 3

PLATE 2

DETERMINATION OF AIRBLAST ATOMIZED SPRAY
STRUCTURE USING STATE-OF-THE-ART LASER DIAGNOSTICS

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ABSTRACT

This paper presents the results of an integrated qualitative-quantitative investigation into the detailed structure of an airblast atomized gas turbine spray at near atmospheric pressure and temperature conditions. Pre-filming airblast atomizer was studied with aviation kerosene as the test fuel. Phase Doppler anemometry was utilised to interrogate droplet size, velocity and number density characteristics while high-energy, pulsed laser sheet illumination technique enabled the visualization of the condition of the liquid at atomizer exit as well as variations in droplet concentration. The spray is found to be generally inhomogeneous in structure and the extent of size, velocity, number density inhomogeneity increases as the axial distance of the measurement plane diminishes. This has implications for the attainment of satisfactory combustion-emissions performance from modern combustors with compact reaction zones.

NOMENCLATURE

D = Droplet diameter, microns
FAR = Fuel-to-air mass ratio
 $\frac{\Delta P}{P}$ = Pressure drop, percent
SMD = Sauter Mean Diameter, microns
 ρ = Density, Kg/m^3
 σ = Surface tension, N/m
 η = Absolute viscosity, Ns/m^2

Subscripts

a = air
f = fuel

1. INTRODUCTION

Combustion of a spray of droplets is widely acknowledged as being a topic of considerable importance for the modern gas turbine engine. This is due to perennial pressures for improvements in fuel economy, flexibility and performance together with the paramount need to protect our environment. Satisfactory fuel-air mixture preparation is necessary not only during sea level ignition and take-off phases of the gas turbine combustor operation but also during intermediate-power cruise and climb phases. In

general, atomization is accomplished easily by creating a high relative velocity between fuel and air and it is usual to aim for good spray performance throughout the operational range of the combustion chamber. Despite the apparent ease with which liquid is atomized, precise mechanism resulting in the formation of a spray of droplets is exceedingly complex and far from adequately understood. As a result atomization research has, to date, largely been confined to dilute sprays operating in simple laboratory conditions. The formation of a spray of droplets from industrial nozzles as well as its subsequent interaction with the aero-thermodynamic environment of the practical combustion zone is, consequently, poorly understood. Limitations of the available diagnostic techniques have been the main impediment in regard to such fundamental studies. Recent advances in non-invasive laser diagnostics is now beginning to offer the prospect of obtaining useful experimental information under realistic conditions concerning near-field spray/droplet performance characteristics. This in turn should help the current efforts relating to the development and verification of dense spray computational codes as well as improvements in fuel injector technology.

Airblast atomizers have been used widely in the modern, high-pressure ratio gas turbine engine because of the particular need for cleaner combustion. The airblast spray is finer in character, and this, combined with the intimate mixing of fuel and air achieved as an integral part of the atomization process, yields a flame with lower levels of luminosity and soot, resulting in relatively cooler liner walls with a minimum of exhaust smoke. In addition the fuel placement in the primary zone is believed to be dictated mainly by the prevailing combustor aerodynamics. In spite of the widespread adoption, the level of knowledge concerning the size, velocity and number density composition of droplets in an airblast spray and the nature of their variation with design-operational variables is far from satisfactory.

The work reported here is a part of continuing effort into airblast atomization research at the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. Some of the previous papers have reported spray performance vis-a-vis the Sauter Mean Diameter as a function of the velocity and density of the atomizing air, the liquid properties, etc., for a range of gas turbine fuel

injectors [1,2]. Visualisation of near-field airblast spray behaviour under varying air pressure conditions is outlined in reference 3. Much work has been carried out elsewhere as well on airblast atomization but in the main it has been confined to comparatively dilute sprays operating at near atmospheric pressure conditions as typified by the study reported in reference 4. As a part of CEC BRITE-EURAM sponsored 'Low Emissions Combustor Technology' programme at Cranfield phase Doppler anemometry and laser sheet illumination techniques have been utilised for gas turbine spray research [5]. The sprays part of the programme was subdivided into two sections - a) Cross-correlation of laser-based diagnostics aimed at examining the level of consistency between experimental droplet data obtained at different research laboratories under nominally identical conditions b) application of phase Doppler Anemometry (PDA) and laser sheet illumination (LSI) techniques to a study of dense, airblast atomized gas turbine spray over a range of air pressures. This paper reports quantitative droplet size, velocity, number density data in conjunction with qualitative, high speed spray-droplet images obtained at near sea-level pressure-temperature conditions. Other data, including high pressure spray measurements, will be reported elsewhere.

2. EXPERIMENTAL DETAILS

Details of the experimental set up used in the study are depicted in figures 1 to 4 and are only briefly described here.

The airblast fuel injector used in this research programme was fully representative of the current gas turbine industry practice and belonged to the generic family of atomizers identified in the literature as the pre-filming type. The injector was in fact of SNECMA design and the outline details are illustrated in figure 1. In this design, the low-velocity fuel is first spread into a, supposedly, thin, circumferentially uniform sheet on an annular surface before being exposed to the shearing action of high-velocity, swirled, inner as well as outer airstreams. Sandwiching of the liquid sheet is designed not only to promote good physical contact between the two fluid streams but also to ensure that the resulting spray of droplets remains largely airborne with minimal deposition on liner walls. The cone angle of the spray is determined by a complex interaction of the swirling atomizing airstreams with the air flow through the cup holes. Figure 2 illustrates the outline of the combustion liner within which the fuel injector usually operates [6].

The fuel injector-cup assembly were installed in a plexiglass plenum chamber which in turn was connected to a near normal pressure and temperature air supply system. Standard aviation kerosine ($\eta = 0.0013$; $\sigma = 0.0277$; $\rho = 784$ - all at 15°C) was the test fuel for the entire study. The fuel and air flow conditions were set using calibrated precision flowmeters and gauges. The spray emanating from the injector was arranged to be horizontal and was directed into a spray collector for disposal. The collection system comprised a cyclone separator driven by a low pressure fan. Figure 3 shows the schematic arrangement of the atmospheric spray facility.

The spray drop sizing and visualizing equipment was supported on a 3-D traversable base. The two sets of equipment were such that they could not be supported and used simultaneously. The laser transmitter and receiver were arranged in the forward scatter mode for drop size determination with the measurement probe volume aligned with the centre of the injector.

Detailed point-wise, measurements on droplets present in a spray are perhaps best obtained by using phase Doppler anemometry (PDA). A single velocity component instrument based upon the above principle and marketed by Aerometrics, Inc. USA was employed in this study. This instrument is an extension of laser Doppler anemometry (LDA) and features three detectors located behind a common aperture of small size - see reference 7 for more details. Use of multiple detectors enables the measurement of the spatial frequency of the scattered interference fringe pattern produced by the passage of droplet through the beam cross-over region. The detectors produce a Doppler burst signal that is similar but it features a phase difference between them. The droplet velocity information is obtained as in a conventional LDA set up whereas the droplet size information is obtained from the phase shift measurements. The use of a rotating diffraction grating enables the imposition of frequency shift thus allowing distinction between negative and positive droplet velocities. The instrument has been interfaced to an IBM PC/AT computer and the individual droplet data is subjected to a sequence of checks before being accepted as a valid sample. Validated droplet size, velocity histograms together with reason for droplets rejected are displayed on the monitor.

High speed imaging is a convenient diagnostic for examining the mechanism of spray formation along with the visualization of the prevailing structures. It can often provide useful insight into the physics of spray atomization and droplet processes. It also has the ability not only to identify the break up length but with suitable image magnification to discriminate between spherical droplets and irregularly shaped ligaments/particles in a liquid spray. In contrast, the laser based droplet characterization techniques do not possess this capability and consequently can yield misleading results. Furthermore, imaging techniques can help identify zones within a spray that are interesting and worthy of detailed probing.

The actual imaging diagnostic employed herein comprised high-intensity, pulsed laser sheet illumination technique. Cylindrical illumination from a Q-switched, frequency doubled, Nd : YAG laser was transformed into a thin sheet through the use of conventional optics as shown in figure 4. The intensity and duration of the pulsed illumination is of critical importance from the view point of spray droplet image quality. A pulse of sufficiently high intensity is desirable in order to penetrate dense, near-field spray zones and hence visualize effectively the processes prevailing in and around the core regions. The duration of the pulse needs to be small enough to "freeze" the fluid motion and hence yield a blur-free image. The laser used in the study was capable of providing pulse of upto 100 mJ energy with 15 nanosecond duration. The beam emerging from the laser is in the form of a collimated cylinder of about 6 mm diameter and this is transformed into a circa 1.5mm thick sheet

using the cylindrical lens arrangement of figure 4. The actual sheet obtained was converging-diverging in nature and the optics were arranged in such a way as to ensure that the centre of injector coincided with the waist section of the sheet. A Hasselblad camera with 400 ASA black and white film was used to capture the spray images and was located in a plane orthogonal to the sheet.

3. RESULTS

As the primary objective of this paper is to provide a better insight into the detailed structure of the airblast atomized kerosene spray, experimental data obtained using the phase Doppler analyser will be presented first followed by that obtained using high-speed laser imaging. Compact reaction zones in modern combustors require spray droplet measurements in the close proximity of the fuel injector - typically within about 25 - 50mm of the atomizer outlet. In general, the choice of actual droplet measurement positions is usually a compromise between such considerations as the spray break-up length, droplet agglomeration, evaporation, combustor primary zone length etc. Measurements too close as well as too far are, usually, avoided because of their vulnerability to undesirable secondary influences. A very large proportion of the earlier Cranfield research has featured characterization at around 40 - 50mm downstream, axial distance in the belief that the mechanism of atomization is by then substantially complete and the secondary processes of agglomeration, evaporation etc have not assumed significant proportions. In this study the measurements were initially made at a downstream distance of 50mm along the spray axis and subsequently repeated at 25mm position.

3.1 Phase Doppler Data

A typical print out from the Aerometrics single-velocity component instrument comprises droplet size and velocity histograms together with the size-velocity correlation. RMS - droplet mean velocity, number density etc information is also provided along with a plot of droplet diameter versus cumulative - volume-by-percent. From this curve can be extracted diameters corresponding to 10%, 50% and 90% cumulative volume points and hereafter they are denoted as D10%, D50% and D90% respectively. Ignition characteristics are, amongst other things, dependent upon the ready availability of a supply of small droplets whilst large droplets are known to affect the emissions performance. D10% and D90% are therefore useful when attention is required to be focussed upon combustor ignition and emissions behaviour respectively. The mean axial velocities corresponding to D10%, D50% and D90% droplet diameters have been obtained from the size-velocity correlation.

Figure 5 illustrates the variation in droplet sizes along a horizontal diameter located at a downstream distance of 50 mm along the spray axis for an air pressure drop of 5% and atomizer FAR of 20%. The outer edges of the spray contain relatively large droplets while the interior regions contain much finer drops and this trend is consistent for the D10% through to D90% diameters covered. As can be observed, there is very little difference between D50% and SMD across the whole of spray cross-section.

The corresponding variation in mean axial velocity for the D10%, D50% and D90% diameters is depicted in figure 6. The outer edges of the spray feature low positive droplet velocities which increase in magnitude as the inner regions of the spray are approached. Right in the centre of the spray there appear to be droplets moving with negative velocities - implying recirculatory motion. The variation in overall mean and RMS velocities is shown in figure 7.

The droplet number density and volume flux data are shown in figure 8 and large spatial variations are evident in both the cases. Furthermore the centre of the spray can be seen to contain very little fuel by volume - by implication spray is probably hollow in nature. Some caution here is necessary as the instrument used in this study is a single-velocity component and may not consequently be detecting all the droplets. The signal quality throughout these measurements was good with the droplet rejection rate generally below about 5%.

The droplet data for the 25mm measurement location is shown in figures 9 to 12. Comparison of figure 9 with 5 reveals SMD, D10% and D50% values to be only marginally different with the further downstream location yielding slightly smaller droplet diameters. D90% values on the other hand are considerably bigger at the 25mm measurement location for bulk of the spray cross-section on the inside. This implies that the larger droplets are continuing to undergo disintegration between the 25 and 50mm measurement planes in the inner spray regions. An examination of figure 10 reveals higher negative velocities (-10 to -17 m/s) with which droplets are moving in the centre of the spray at the 25mm location in comparison with the 50mm location (-6 m/s max). This would seem to suggest the existence of a swirling droplet movement pattern that decays with an increase in downstream distance ie with drag. Mean axial velocities can be observed to decay with downstream distance too - contrast figure 11 with figure 7. The volume flux, number density plots still indicate the existence of a hollow region in the centre of the spray. The peak droplet number density drops as the measurement location distance increases.

3.2 Laser Imaging Data

Plate 1 illustrates the spray visualization data obtained for an atomizer air pressure drop of 5 percent and kerosene FAR of 10 percent. Large-scale, bulk spray features were recorded using comparatively low primary (image) magnification (circa 0.4) and they confirm the somewhat hollow nature of the spray in the centre - plate 1(a). In addition, they also reveal the existence of regions of widely varying droplet number density. Visualization of local features as well as droplets was conducted using higher image magnification camera optics and typical images obtained are shown in 1(b) and (c). It is evident from these images that liquid is already broken up into droplets by the time it emerges from the atomizer outlet. The maximum primary magnification attained during this study was circa 4 with a minimum sheet thickness of around 1.5mm.

Plate 2(a) illustrates the effect of laser sheet quality upon spray droplet image definition. The poorer quality image relates to a laser sheet thickness of around 6 - 7mm while the better

quality image was obtained with circa 1.5mm thick sheet. The extent of droplet image co-incidence in a spray increases with an increase in sheet thickness with a consequent degradation in image quality. Illustrated in 2(b) are images from a dilute and a dense region within the same spray and clearly there is a large variation in local droplet concentrations. Problems of co-incident images can be minimised in dense spray zones and better quality images obtained by employing even thinner sheets vis-a-vis longer focal length cylindrical lenses.

Although not reported here, the images obtained have been successfully analysed by collaborating partner for droplet characteristics. For satisfactory digitisation, out-of-focus images (due to limited depth-of-field, non-uniform illumination, etc.) and background noise (contributed by multiple optical surfaces) require to be minimised.

4. CONCLUDING REMARKS

The combination of phase Doppler anemometry and pulsed, laser sheet imaging for determining the structure of an airblast atomized spray has turned out to be a satisfactory one. This assertion is supported by the foregoing sections of the paper featuring detailed experimental data. The two diagnostics complement each other to yield a balanced qualitative-quantitative insight into airblast spray structure. Further refinements of laser imaging are planned to enhance its dense spray capability. As a consequence the prospect of identifying spray regions that are safe, interesting and worthy of detailed, point-wise, probing should become somewhat less remote.

The airblast atomizer results presented in this paper reveal the spray structure to be generally inhomogeneous and this has implications for the realisation of satisfactory combustion-emissions performance. Unsatisfactory spray-droplet evaporation performance together with inadequate fuel vapour-air mixing would affect the flame characteristics with consequences for soot and other pollutant species.

The following specific conclusions can be drawn from this study:

1) The structure of airblast atomized spray studied comprises slow moving, larger droplets on the outside while the inner regions contain small, faster moving droplets.

2) Located right in the centre of the spray is a low droplet number density region featuring negative velocities.

3) Measurements reveal the smaller droplet formation process to be substantially complete by the 25 mm sampling location while the larger droplets in the inner spray regions appear to undergo further break-up between the 25 and 50 mm locations.

5. ACKNOWLEDGEMENTS

The financial support for this study was provided by CEC under the BRITE/EURAM Low NO_x Combustor Technology Programme with SNECMA providing the fuel injector. The authors gratefully acknowledge this support as well as the help of Cranfield colleagues in making this study and paper possible.

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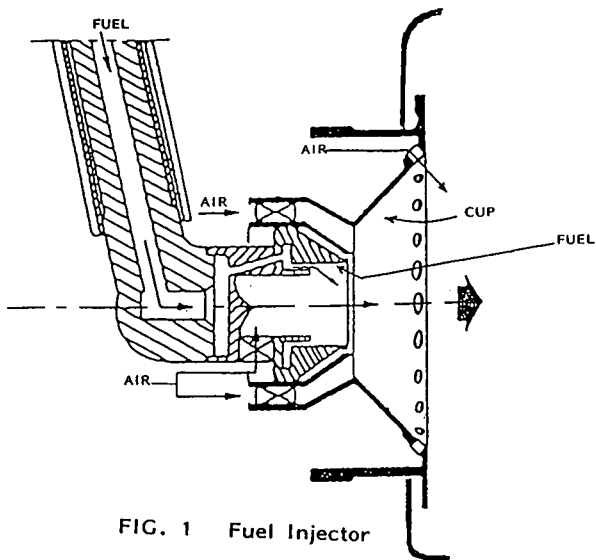


FIG. 1 Fuel Injector

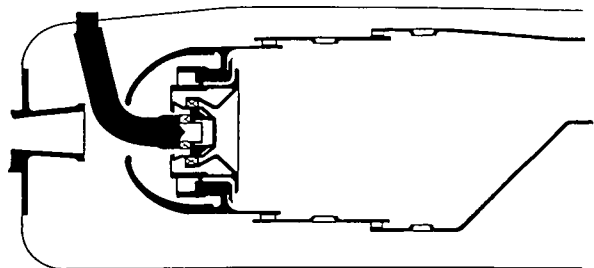


FIG. 2 Combustion Liner

FIG. 3 FUEL SPRAY RIG SET UP

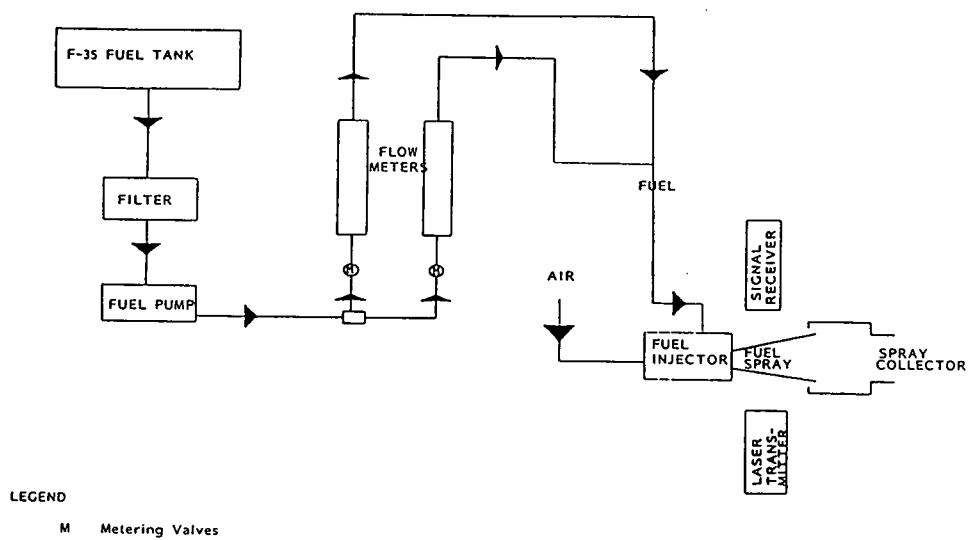
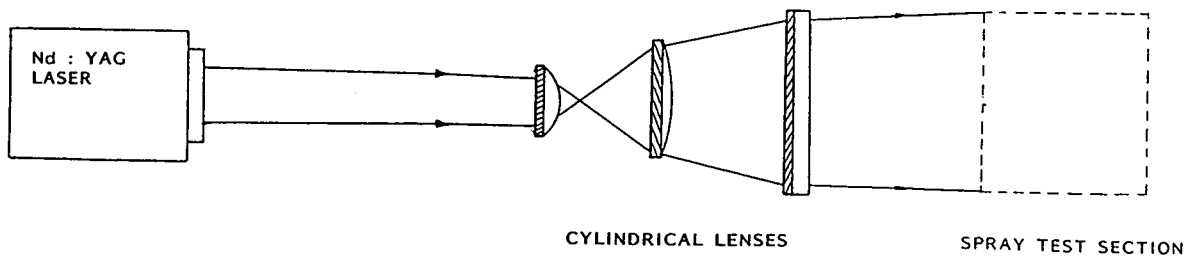


FIG. 4 SCHEMATIC OF SPRAY SHEET VISUALIZATION SET UP

Fig.5 Drop Sizes Distribution
50mm d/s, $\tilde{P}/Pa=5\%$, FAR=20%

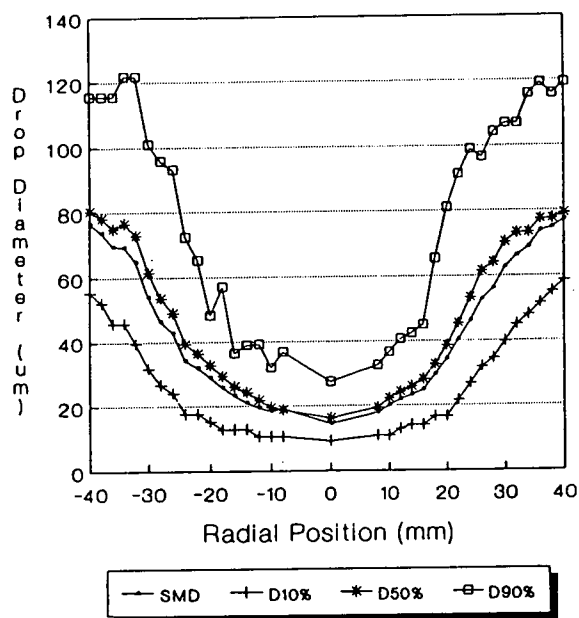


Fig.6 Drop Velocity Distribution
50mm d/s, $\tilde{P}/Pa=5\%$, FAR=20%

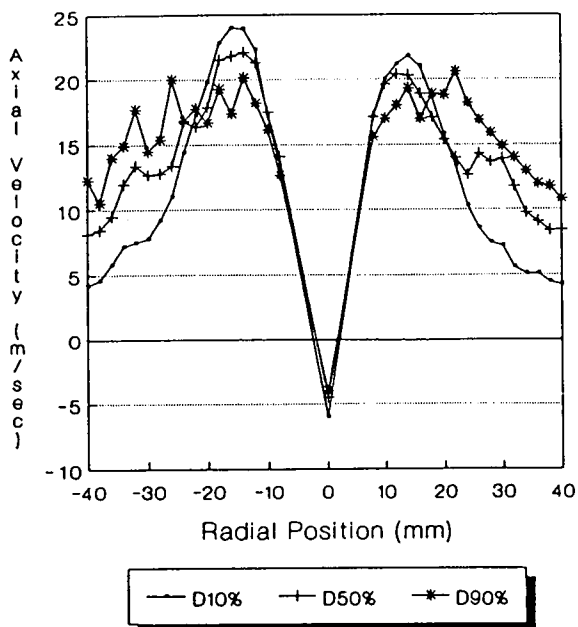


Fig.7 Mean Velocity Distribution
50mm d/s, $\tilde{P}/Pa=5\%$, FAR=20%

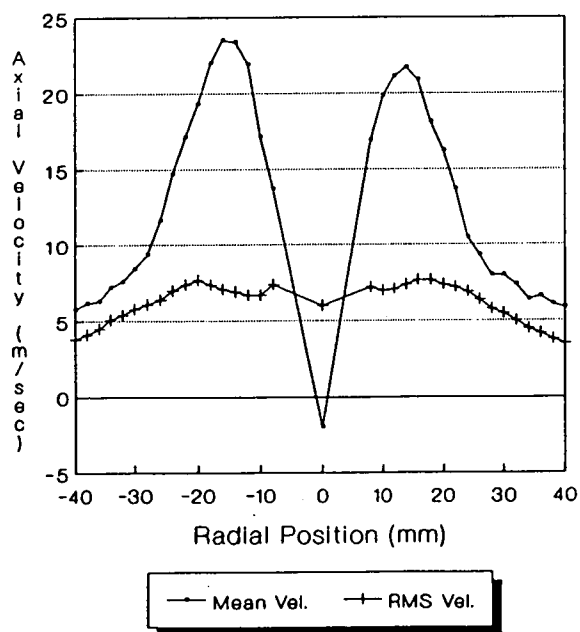


Fig.8 Concentration Distribution
50mm d/s, $\tilde{P}/Pa=5\%$, FAR=20%

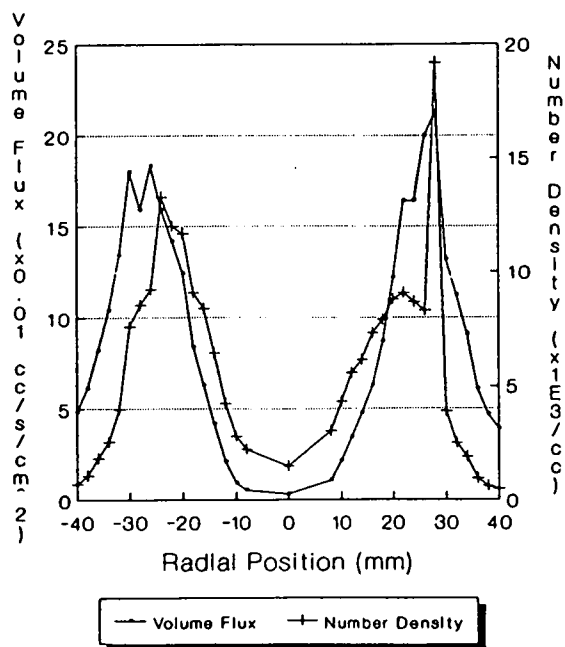


Fig.9 Drop Sizes Distribution
25mm d/s, $\dot{P}/P_a=5\%$, FAR=20%

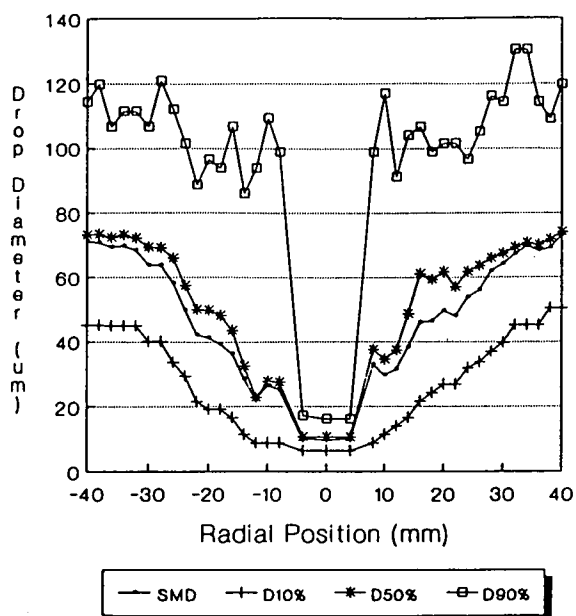


Fig.10 Drop Velocity Distribution
25mm d/s, $\dot{P}/P_a=5\%$, FAR=20%

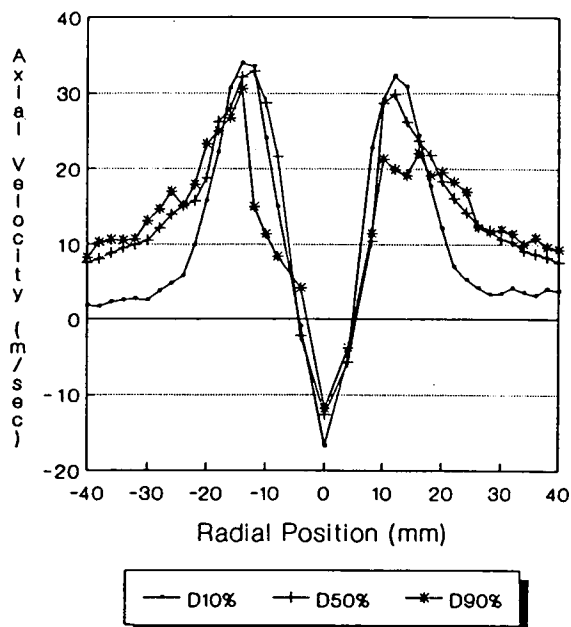


Fig.11 Mean Velocity Distribution
25mm d/s, $\dot{P}/P_a=5\%$, FAR=20%

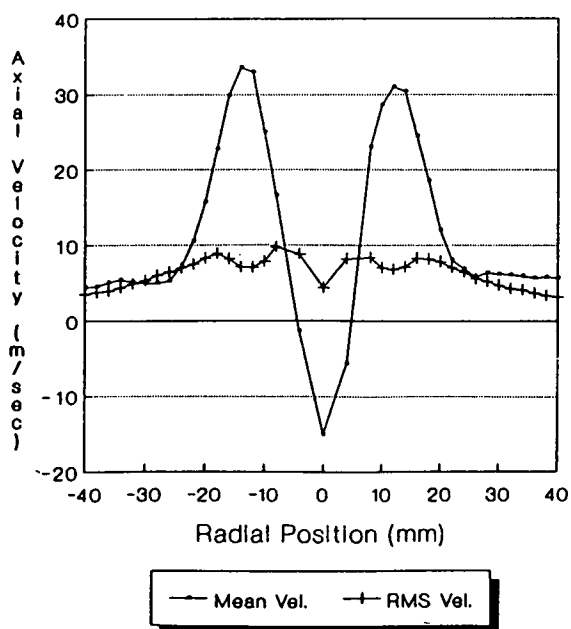
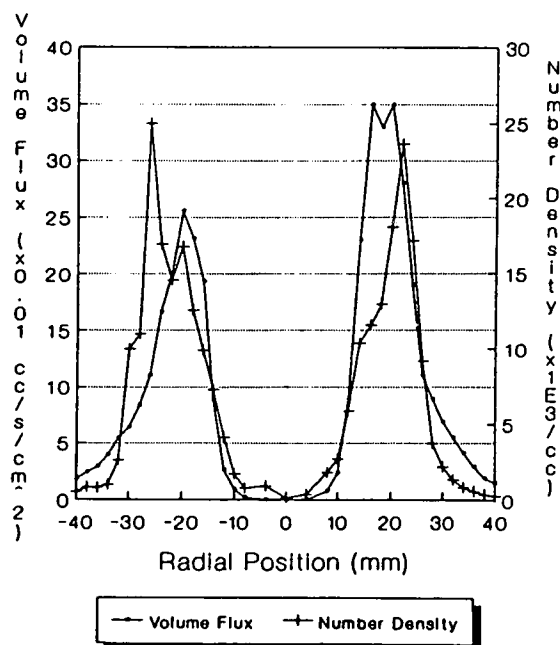


Fig.12 Concentration Distribution
25mm d/s, $\dot{P}/P_a=5\%$, FAR=20%

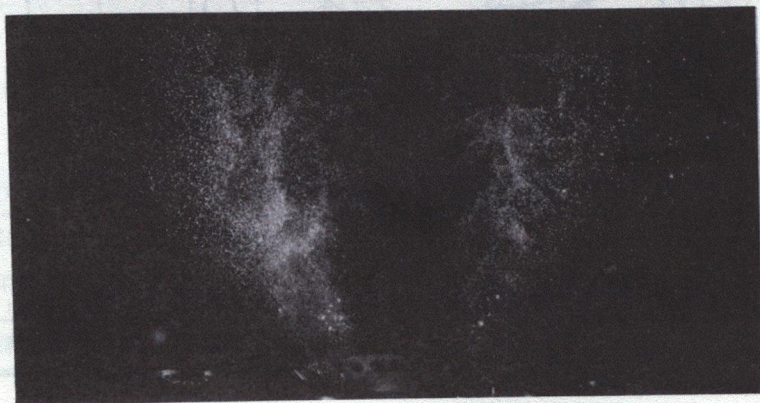




(c)



(b)



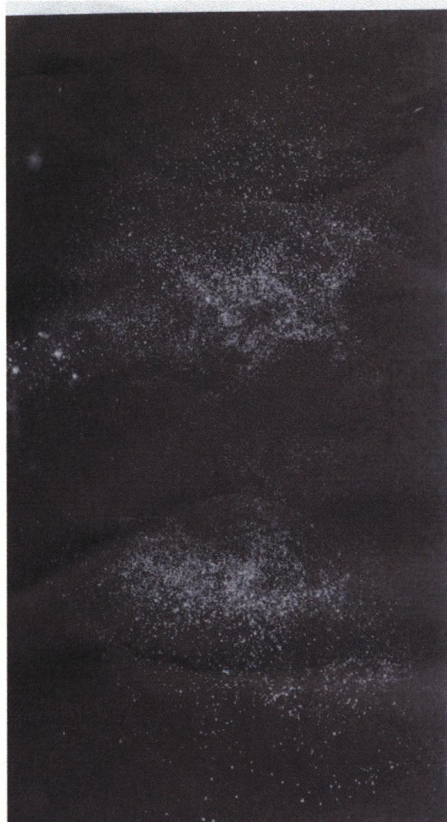
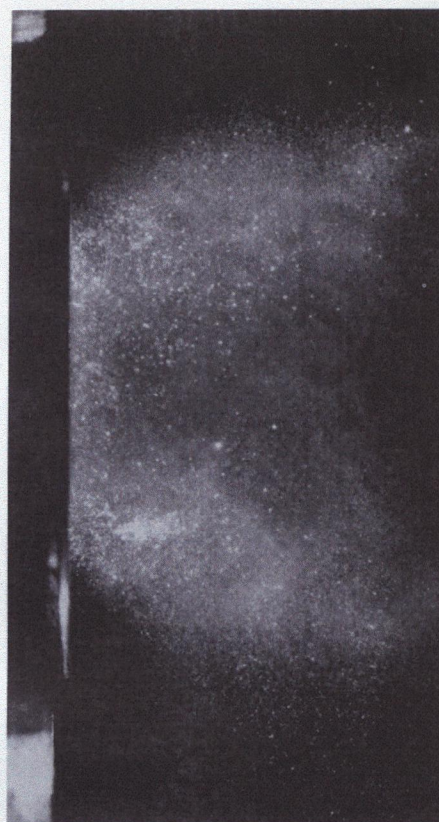
(a)

PLATE 1 PULSED LASER SHEET ILLUMINATION

PLATE 2

(a)

Effect of Sheet Quality



(b) Effect of Imaging Position

CROSS-CORRELATION OF THREE DROP SIZING TECHNIQUES ON AN AIRSPRAY FUEL INJECTOR

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ABSTRACT

Research into the control of emissions from gas turbine combustors demands high temperature and pressure where not only are test costs high but also the application of diagnostic tools to the interior of the combustor is technically difficult. Under the CEC BRITE/EURAM - funded Low Emissions Combustor Technology programme, the limitations of non-intrusive laser diagnostic techniques have been explored.

1.0 INTRODUCTION

In order to establish the reliability and accuracy of the sophisticated optical instruments used within the BRITE/EURAM Low Emissions Combustor Technology programme, a cross correlation exercise has been carried out. This will enable the selection of the best instruments for use in further experiments. The partners involved and the instruments used are listed in table 1.

The airspray injector was mounted in a perspex airbox, and was not removed during the experiment. The airbox and injector were sent to each partner in turn. Kerosene was used by all participants and a sample from each partner has been analysed.

Three different measurement techniques were compared, Phase Doppler Anemometry (PDA), Laser Diffraction (LD) and Amplitude

Doppler (AD), within this comparison the results from three commercial PDA instruments were collated.

2.0 TEST FACILITIES

A description of the test facilities used by each of the partners is given below. All of the rigs operate at atmospheric pressure and the spraying medium was kerosene.

2.1 CRANFIELD

The airbox is mounted at the outlet of a compressed air supply and orientated to spray horizontally. The transmitter and receiver are mounted on a levelled bench, which has a 3-D traverse. This enables the PDA optics to be moved relative to the atomiser. The system is set up for a 30° off-axis collection angle in forward scatter, with the transmitter and the receiver each located at an angle of 15° to the bench. Cranfield have a 1-component Aerometrics PDA which uses a 10mW HeNe laser.

2.2 DLR

In the DLR test facility the airbox is mounted to spray vertically into a cylindrical exhaust system. The transmitter and receiver are mounted in the same plane and are able to move in the x-y directions.

Participant	Technique	Instrument
Rolls-Royce	Phase Doppler Anemometry Laser Diffraction	two component Aerometrics Malvern
Cranfield Institute of Technology	Phase Doppler Anemometry	one component Aerometrics
D.L.R.	Phase Doppler Anemometry Holography	two component Dantec
Rouen University	Amplitude Doppler	one component TSI
University of Karlsruhe	Phase Doppler Anemometry Laser Diffraction	two component Aerometrics Malvern

TABLE 1

The rig itself could be moved in the vertical z-direction. The 2-component Dantec PDA system was set up to collect at 68.8° off-axis forward scatter, and uses a 4W Argon ion laser.

2.3 KARLSRUHE UNIVERSITY

At Karlsruhe University the airbox was mounted such that it sprayed vertically into the fuel spray collecting and settling container. The airbox is mounted on a 2-D traverse and the PDA system is fixed in position. The receiver is set up to collect at 30° off-axis in forward scatter. The PDA system at Karlsruhe University is an Aerometrics 2 component and is used with a 4W Argon ion laser. On the same facility a Malvern laser diffraction instrument is mounted 30° from the PDA transmitting optics and allows simultaneous measurements to be taken with both instruments.

2.4 ROLLS-ROYCE

In the test facility at Rolls-Royce the transmitter and receiver of the PDA instrument are housed in air tight boxes which are continuously purged during the running of the rig for flameproofing. The receiver is set at an off-axis forward scatter angle of 30°. The air box is mounted on a 3-axis traverse, when taking PDA measurements it is the spray that moves relative to the probe volume. It is possible to rotate the rig through 360°, thus allowing the measurement of the third component of velocity. A 2W argon ion laser is used linked via a fibre optic cable to the input of the transmitter, Rolls-Royce used a 2-component Aerometrics PDA instrument. Also mounted in the fuel spray facility is a Malvern laser diffraction instrument. The airbox can be rotated in order to take measurements in the same plane as the PDA measurements.

2.5 ROUEN UNIVERSITY

The airbox at Rouen University was orientated to spray horizontally. The photomultiplier was set up to collect at 21° off-axis in forward scatter. Rouen have a TSI Amplitude (Top Hat) Doppler system this uses the green and blue beams from an Argon ion laser. Rouen measured 3 points per traverse (see section 5.1) and because of this the problem of traversing the airbox was not as crucial.

3.0 MEASUREMENT TECHNIQUES

All three of the techniques used are non-intrusive laser based techniques. What follows is a brief description of each, accompanied by the appropriate references for further details.

3.1 PHASE DOPPLER ANEMOMETRY Bachalo, Houser (1984).

A laser is used to produce a single intense beam of highly collimated monochromatic light. This beam is split into two parallel beams of equal intensity which are subsequently focused to a common intersection, this forms the measurement volume. Within the measurement volume a system of fringes are formed due to the optical interference of the two beams. The spacing of the fringes (d_f) depends on the angle of intersection of the beams (θ) and the wavelength (λ) of the laser light.

$$d_f = \frac{\lambda}{2\sin(\theta/2)} \quad (1)$$

As a small particle crosses the measured volume light will be scattered in all directions. The signal that is received at the detectors is referred to as a Doppler burst. The Doppler frequency (f_d) is the result of the particle crossing successive light and dark fringes, and is related to the particle velocity by the expression

$$V = d_f \times f_d \quad (2)$$

The phase of the laser doppler signal varies with the angular position of the detector, the phase difference between two fixed detectors is proportional to the particle diameter. The size of the particle, therefore is determined from the difference in phase between the Doppler burst signals detected by each photomultiplier tube in turn. Using three photomultiplier tubes in the receiving optics provides two pairs for cross checks, extends the dynamic range of the method and, because the phase shift is related to the curvature of the particle, the sphericity of the particles can be determined.

3.2 LASER DIFFRACTION Swithenbank, Beer, Taylor, Abbot, McCreath (1977).

This instrument is based on the Fraunhofer diffraction theory of a collimated laser beam scattered by moving drops. A collimated laser beam is directed into the spray. The light energy scattered by the moving drops in the whole path length of the beam across the spray is collected by a Fourier transform lens and focused onto a photodiode array detector composed of 31 semicircular, concentric detectors. Since the calculations of drop size relies upon the relationship between size and light scattering angle, the technique relies upon light being scattered only once before reaching the detector. This sets an obscuration limit of around 60% for accurate data. The dropsize is calculated from the measured light energy distribution by performing a least squares analysis to determine the best-fit size distribution parameters. The dropsize distribution model has to be pre-selected, from Model-Independent, Log-normal or Rosin Rammler.

AMPLITUDE (TOP HAT) DOPPLER Allano, Gouesbet, Grehan, Lisiecki (1984).

The particle velocities are measured by Laser Doppler Velocimetry (LDV) using the green wavelength from an Argon ion laser. The green beam is split in two and the measurement volume is at the intersection of the two beams. Superimposed on this probe volume is the blue beam. From the use of Lorenz-Mie theory the properties of the light scattered by a Mie scatter center illuminated by a plane wave can be predicted. A monotonic relationship exists between the scattered signal and particle diameter. The Gaussian blue beam is corrected to a TOP HAT profile with a metal-coated absorbing filter to eliminate any drop trajectory ambiguities. The blue beam is enlarged so that the probe beam diameter is about twice the particle diameter.

4.0 TEST CONDITIONS

The operating conditions for the aerospray fuel injector were repeated by each of the partners and similarly the measurement planes. Table 2 outlines the four operating conditions that were used and Table 3 lists the parameters that were measured by each partner.

CONDITION 1	ΔP 5% of atm	FAR 20%
CONDITION 2	ΔP 5% of atm	FAR 10%
CONDITION 3	ΔP 3.5% of atm	FAR 20%
CONDITION 4	ΔP 3.5% of atm	FAR 10%

TABLE 2 OPERATING CONDITIONS

At each condition measurements were taken across a diameter perpendicular to the burner feedarm in planes 25 and 50mm downstream of the injector exit.

The last group to receive the airbox were Karlsruhe University. During their testing the atomiser showed a strong asymmetry at all the operating conditions, this asymmetry was not present in the data of the other partners. There was no visible evidence of blockage, however, by using a microscope unit it was found that some fluff was blocking three exit air holes of the atomiser. This was removed using compressed air.

After the removal of the fluff, there was only time to repeat one of the test conditions, this traverse now exhibited a nearly symmetrical spray pattern. By comparing the traverse before and after the fluff was removed the agreement of the profiles on one half of the spray was excellent. It has been possible to use the data from the negative radial positions to compare with the other partners.

5.0 RESULTS

5.1 LDA BASED TECHNIQUES

This section will compare the results from the four Phase Doppler Analysers and Amplitude Doppler technique. The condition that has been chosen to be discussed in full is the one at which Karlsruhe University

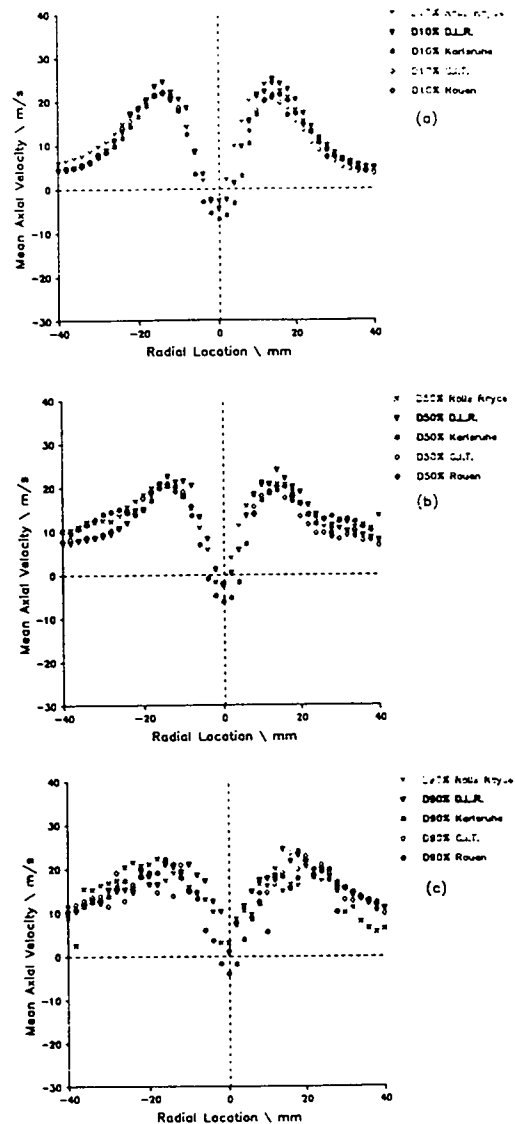


FIGURE 1 AXIAL VELOCITY (a) D10%, (b) D50%, (c) D90% CONDITION: ΔP 5%, FAR 10%, 50mm d/s

Partner	Instrument	Parameters Measured
Rolls-Royce	2 Component Aerometrics	Axial Radial and Tangential Velocities. Drop size.
	Malvern	Drop size
Cranfield Institute of Technology	1 component Aerometrics	Axial Velocity Drop size
D.L.R.	2 component Dantec	Axial Radial and Tangential Velocities. Drop size.
Rouen University	1 component Amplitude Doppler	Axial Velocity Drop size
University of Karlsruhe	2 component Aerometrics	Axial, Radial and Tangential Velocities. Drop size.
	Malvern	Drop size

TABLE 3 MEASURED PARAMETERS

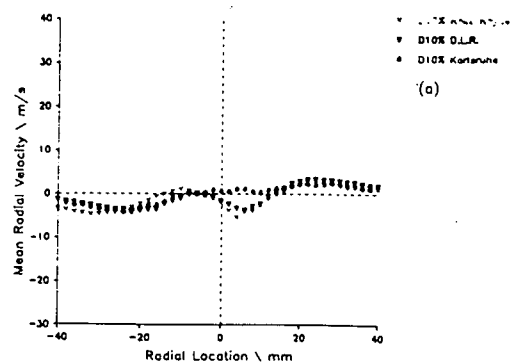
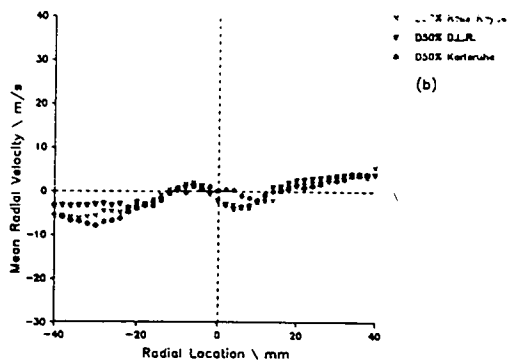
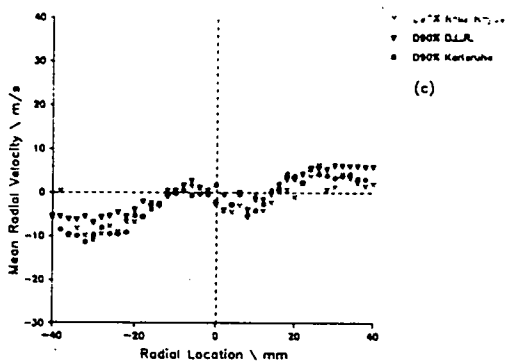


FIGURE 2 RADIAL VELOCITY (a) D10%, (b) D50%, (c) D90%
CONDITION: DELTA P 5%, FAR 10%, 50mm d\

were able to repeat their measurements on the unblocked airspray, $\Delta P 5\%$, F.A.R. 10%, 50mm downstream. Data were collected at 2mm increments to + and - 40mm from the burner centre line. The data collection rate of Rouen's Amplitude Doppler technique is very slow, around one hour per point and this limited the points measured per traverse to three, at radial positions +8mm, +18mm and +28mm.

The drop size has been presented as the mass undersize parameters, D10%, D50%, D90% in order to assist in understanding where differences in results arise. The velocity means and RMS values corresponding to these three drop sizes have been plotted against radial location.

Figures 1 to 4 show the complete set of results for the condition $\Delta P 5\%$ F.A.R. 10% measured at 50mm downstream. The velocities for the size classes D10%, D50% and D90% are shown in Figures 1, 2 and 3 respectively. Figure 4 shows the drop diameter plots again for each size class.

Looking at figures 1, 2 and 3 the similarity in the results is clear. There

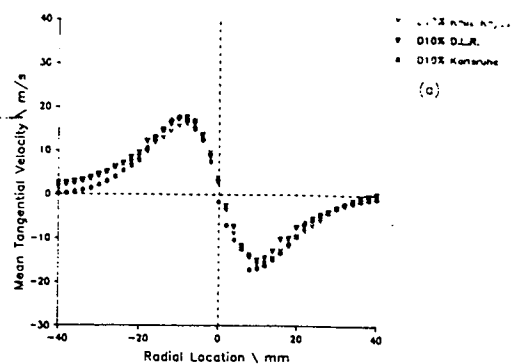
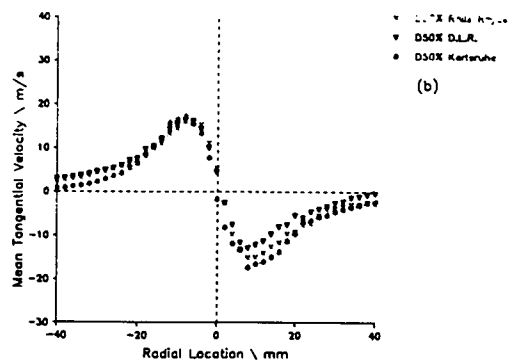
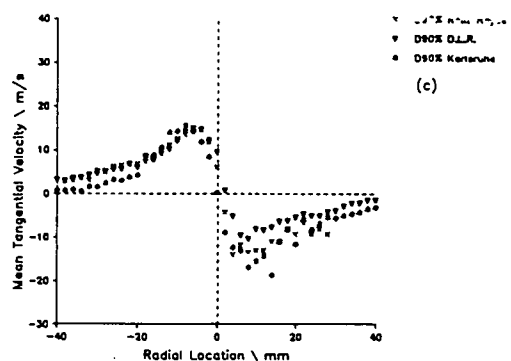


FIGURE 3 TANGENTIAL VELOCITY (a) D10%, (b) D50%, (c) D90%
CONDITION: DELTA P 5%, FAR 10%, 50mm d\

are slight variations but the general trends are in agreement. The axial velocity profile shows a small recirculation still exists in the centre at 50mm downstream. The profile is very symmetrical with peak velocities occurring at approximately 17mm either side of the centre line. There is a small component of radial velocity acting outward from the centre line of the burner. The tangential velocity peaks 10mm either side of the centre line, dropping towards zero at the edges of the spray. The RMS velocities are very similar for all three components, not rising above 10ms^{-1} at any point in the traverse. Comparing the velocity profiles of the 3 dropsizes classes, the tangential velocity profile is similar for all three. The radial velocities at the outer edges increase slightly for the larger drops, D90%. The axial velocity profile is flatter for the two larger size classes; for D50% there is a smaller recirculation in the centre and for D90% drops only Karlsruhe have measured any drops with negative velocities. At the outer edges of the spray the D50% and D90% drops are moving faster than the smaller D10% drops. Both of these observations are as expected with the smaller drops following the air velocities

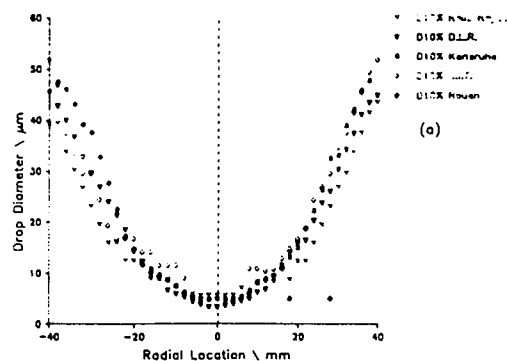
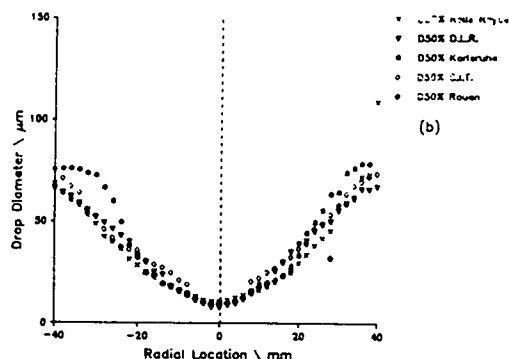
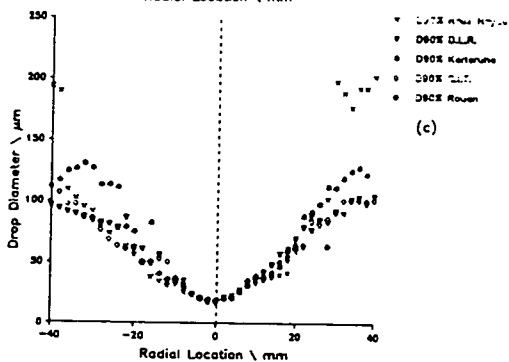


FIGURE 4 DROP DIAMETERS (a) D10%, (b) D50%, (c) D90%
CONDITION: DELTA P 5%, FAR 10%, 50mm d/s

and the larger drops travelling ballistically.

At all the test conditions there is a lot more scatter in the D90% plots both for drop size and velocity plots. This is due to the small number of drops at the larger end of the distribution compared with D50% and D10% regions. In some cases there were as few as three or four large drops contributing to the D90% value. An example of this will be shown later in this section.

Figure 5 illustrates an instrument set up problem. By looking at the D90% plot one can see that the Rolls-Royce values at the edges of the spray are much greater than the other partners. There is a difference in the D90% value between points 16 and 17, at -8 and -10mm, of 182μm. This can be explained by the instrument set up change shown in table 4.

By reducing the maximum diameter value from 210μm to 160μm a few large drops that still exist have been excluded and this has greatly influenced the D90% value. Figure 6 shows further evidence of this by illustrating the % Number and % Volume distributions for the -10mm point. There

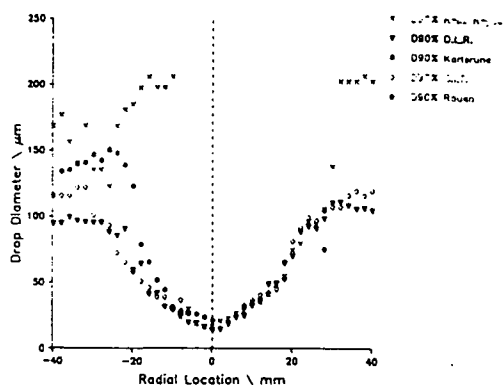


FIGURE 5 DROP DIAMETERS - D90%
CONDITION: DELTA P 5%, FAR 20%, 50mm d/s

Rad Loc./mm	Instrument Setting Diameter Range/μm	D90%/μm
-12	6 - 210	197.3
-10	6 - 210	205.6
-8	4.6 - 160	23.6
-6	4.6 - 160	29.9

TABLE 4

appear to be only 3 large drops present above 180μm with the majority of drops having diameters below 80μm.

Although these large drops are few in number, when looked at in terms of % volume the d^3 effect is very large. It is this cluster that determines the D90% value. The presence of these large does not have any influence on the values of D50% or D10% but an area of concern arises when using the volume flux information. In this case by omitting these large drops the volume flux results are severely biased. Particular care must be taken when changing the diameter range during a traverse, especially if the volume flux information is to be used. Additionally, the source of such drops and their relevance to the spray must be considered.

At all test conditions the agreements between the partners for drop size are good, with the exception of the Rouen drop size data. The dropsize measurements are generally lower than those measured by the other partners. This is presumed to be due to the narrow drop size range of the instrument which is restricted by the probe beam diameter. Figure 7 gives an example of the dropsize plot for one condition and

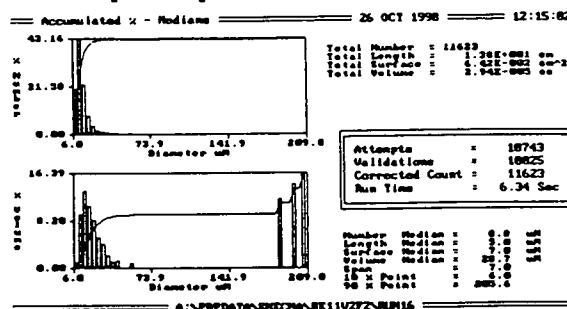


FIGURE 6 ROLLS ROYCE RADIAL LOCATION -10mm
CONDITION: DELTA P 5%, FAR 20%, 50mm d/s

figure 8 shows a plot of the maximum diameter settings across the traverse for the same condition. The maximum diameter of the amplitude doppler especially at the 25mm downstream conditions, are lower than the other partners implying that they are not recording a number of large droplets which have been seen to exist in the data of the other partners.

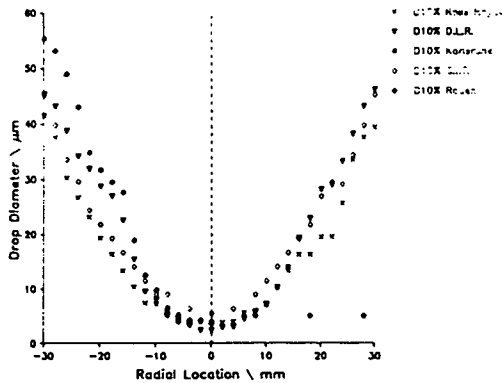


FIGURE 7 DROP DIAMETERS - D10%
CONDITION: DELTA P 3.5%, FAR 10%, 25mm d/s

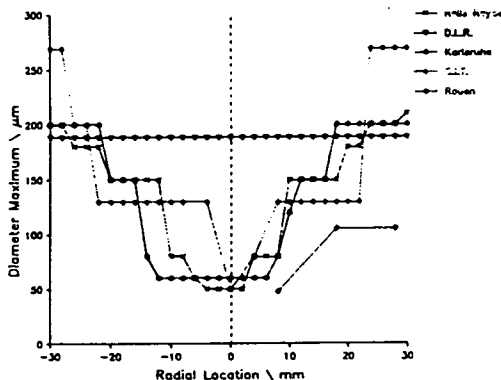


FIGURE 8 MAXIMUM DIAMETER SETTINGS
CONDITION: DELTA P 3.5%, FAR 10%, 25mm d/s

At 25mm downstream the velocities correlate very well, again showing more scatter for D90% values. However, for the drop size data the D90% values exhibit a more random distribution than D50% and D10%. Figure 9 shows the worst example. Looking at the D90% plot none of the partners results show any particular trend in the distribution of the data. What is quite surprising is the size of some of these drops particularly in the middle of the spray. Drops with diameters of the order of 100μm to 150μm, in a couple of cases even greater than this. These large drops, however, have disappeared from the centre of the spray by 50mm downstream. At this downstream plane the larger drops probably have been centrifuged to the edges of the spray cone. The insensitivity of the velocity results, figure 10, indicates there is little correlation between drop size and velocity.

5.3 MALVERN VS PHASE DOPPLER ANALYSER

Two of the partners, Rolls-Royce and Karlsruhe University, took Malvern measurements on the same spray at the same conditions as the PDA measurements. Below is a summary of the results from both partners.

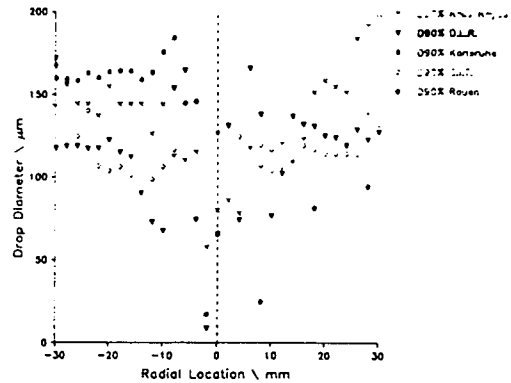


FIGURE 9 DROP DIAMETERS - D90%
CONDITION: DELTA P 3.5%, FAR 20%, 25mm d/s

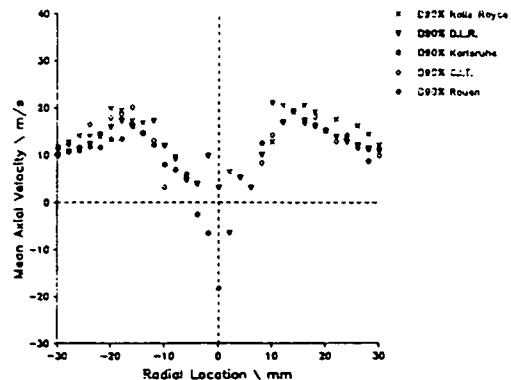


FIGURE 10 AXIAL VELOCITY - D90%
CONDITION: DELTA P 3.5%, FAR 20%, 25mm d/s

There are two methods by which the Laser Diffraction (LD) measurements can be compared with PDA results. A brief description is given below, for further reading please refer to the following: Dodge, Rhodes & Reitz (1987), Dodge (1987).

The laser diffraction instrument measures a line-of-sight average through the complete spray. It registers a signal proportional to the population of drops within the volume defined by the intersection of the laser beam and the spray, this is referred to as a spatial average. The phase doppler analyser, samples a very small volume and registers a signal proportional to the number of drops passing through this volume, known as temporal sampling. To compare the LD and PDA measurements it is necessary initially to convert the PDA data to spatially averaged. Then either to average the PDA results into line-of-sight data or deconvolve the LD line-of-sight into point data, Hammond (1981).

Table 5 shows the planes and conditions that were measured at Rolls-Royce using the Malvern instrument. For this exercise the PDA measurements were converted to a single line-of-sight value for comparison. The method used was that given by Jackson and Samuelsen (1986). The line-of-sight $D_{3,2}$ value is given by

$$D_{3,2} = \frac{\sum_j D_{3,2,j}^3 (N_j/V_j)L_j}{\sum_j D_{3,2,j}^2 (N_j/V_j)L_j} \quad (3)$$

where $D_{j,0}$ and $D_{j,1}$ are the volume mean and area mean diameters of the j th ring. For equally spaced points through a diameter the L_j values are equal and can be ignored. For comparison with LD the spatially averaged values of $D_{j,0}$ and $D_{j,1}$ are used in the above calculation.

Table 5 allows a comparison of the Malvern data with the Aerometrics to be made. At all conditions, except one, the equivalent line-of-sight measurements for the PDA were higher in value than the LD data. Included in table 5 are the % obscuration values at each condition. Figure 11 plots the difference between the PDA D_{32} and the LD D_{32} (DELTA) against % obscuration. With the exception of two points there is a correlation between the DELTA value and % obscuration. As the obscuration increases, ie as the spray becomes denser, then the difference between the PDA and the LD values increase. This is consistent with the effect of increasing secondary scattering with obscuration.

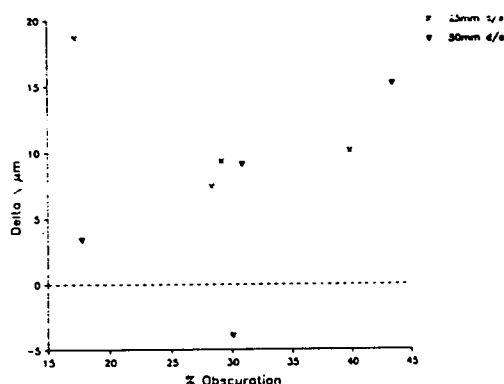


FIGURE 11 MALVERN \ PDA DATA

Since this will increase the intensity of light reaching the outer rings of the detector which correspond to smaller drop sizes, scattering angle being inversely proportional to drop diameter.

The Malvern instrument at Rolls-Royce is model no. 2605LC the beam diameter was 9mm and the focal length of the receiving

lens was 300mm. The analysis used was the Model Independent.

These results are from the measurements taken by Rolls-Royce. The results from the Karlsruhe comparison, involving the Malvern and Aerometrics, are to be reported separately.

6.0 DISCUSSION

6.1 PDA

One aspect that has been highlighted in the analysis of all the results, is the importance of setting the instrument up correctly. This applies to the Aerometrics instruments in particular since these are currently used with a counter processor. When using the Aerometrics PDA it is possible to optimise the settings for diameter range, velocity range, PMT voltages and velocity offset (ie the speed of diffraction grating) at each point in the traverse. An example of this would be as one moved towards the centre of the spray the drops are smaller and the diameter size range could be reduced. By setting the diameter maximum too low it is possible to omit any larger droplets present from the subsequent analysis of the data. One effect of this would be to severely bias the volume flux calculations. Because these large drops tend to be few in number, omitting them from the analysis has little or no effect on many of the other parameters ie D_{32} , D_{50} , velocity-size distributions. When looking at the median plots the $D_{90\%}$ value is the only one effected. One solution to this would be to leave the drop-size range as wide as possible. However, the PDA instrument provides correlated velocity/size data and can therefore provide a measure of the gas velocity as well as the spray velocity. If one was interested in these gas velocities then the instrument should be configured to obtain detailed information on the smallest particles. These two examples emphasise the need to set the instrument up according to the nature of the experiment and great care in doing this must be taken. The Dantec PDA instrument uses a Burst Spectrum Analyser, which requires no changes to be made to the set up during the traverse.

Condition	Aerometrics equivalent line-of-sight value $D_{32} \mu\text{m}$	Malvern $D_{32} \mu\text{m}$	Obscuration (Malvern)	DELTA Aerometrics-Malvern
Δ P5% FAR 20% 25mm d/s	46.11	35.95	39.8%	10.16
Δ P5% FAR 20% 50mm d/s	51.46	36.27	43.4%	15.19
Δ P3.5% FAR 20% 25mm d/s	56.24	48.80	28.3%	7.44
Δ P3.5% FAR 20% 50mm d/s	57.01	47.90	30.8%	9.11
Δ P5% FAR 10% 25mm d/s	42.82	33.47	29.1%	9.35
Δ P5% FAR 10% 50mm d/s	30.49	34.38	30.0%	-3.89
Δ P3.5% FAR 10% 25mm d/s	61.81	43.10	17.2%	18.71
Δ P3.5% FAR 10% 50mm d/s	47.29	43.87	17.7%	3.42

TABLE 5 MALVERN \ PDA DATA

The value of drop size at the 90% mass undersize point seems to be an unreliable figure to look at. As we have seen it depends largely on the instrument setting and can be influenced by two or three large drops. It could give a false impression of the droplet distribution and should be used in conjunction with the actual droplet distribution. It is not recommended as a valuable parameter when looking at sprays of this type.

6.2 AMPLITUDE DOPPLER

The major drawback of the "Top Hat", Amplitude Doppler system, especially in comparison to the commercial PDA instruments, is the length of time required to collect the data at each point. This is a recognised shortcoming targeted for improvement.

Another limiting factor was the narrow drop size range of this instrument, a ratio of 15 between smallest and largest particles, for two different probe beams. The ratio of 15 has since been improved to 100 with the use of a logarithmic amplifier.

6.3 LASER DIFFRACTION vs PDA

These two instruments have applications which are quite remote from each other and because of this it is not really feasible to compare the two. To either use LD to obtain point measurements by deconvoluting line of sight data, or to use PDA to get line-of-sight data are both time consuming exercises and not worthwhile.

If a detailed mapping of the spray is required then the obvious choice is PDA where both velocity and drop size information are available. If, however, overall dropsize information only is required and a line-of-sight average would suffice then LD would be the choice, cutting down the testing and processing times. However the spray density limit of LD is much lower than for PDA since secondary scattering from a full spray diameter will have a lower threshold than the single drop criterion in the very small probe volume of the PDA instrument. The choice of instrument is dictated entirely by the type of data required for any given application.

7.0 CONCLUSIONS

Despite the use of horizontal and vertical spray rigs, the geographical location of the participants and the spread of measurements over almost two years, the agreement in both drop size and velocity results is excellent. This exercise has generated a high degree of confidence in the measurement techniques and in the comparison of data from different research facilities, which could be involved in future collaborative programmes.

One point that has emerged from this exercise is that care must be taken with the instrument set up parameters. This needs to be done keeping in mind the overall aim of the experiment.

Although PDA and Amplitude Doppler methods generally agreed well the large discrepancy in data rates makes PDA the more attractive technique.

In the comparison of PDA and Laser

Diffraction (Malvern) data, it should be borne in mind that the laser diffraction method is a technique that is applicable in different situations to that of the PDA. The PDA is ideally suited to detailed spray modelling where drop velocities as well as sizes are required. The Malvern laser diffraction instrument is very repeatable and fast for examining overall spray behaviour, but gives size distribution only. Because of these fundamental differences in use and in measuring technique it is hard to compare the two instruments.

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Examination of Detailed Structure of a
Pressure Atomized Spray Using Laser Diagnostics

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ABSTRACT

The detailed structure of a kerosine spray emanating from a typical gas turbine starter jet is interrogated under sea-level pressure-temperature conditions. Phase Doppler anemometry and pulsed laser sheet illumination were the diagnostics employed to obtain a balanced quantitative-qualitative insight into the behaviour of the pressure atomized spray. The spray studied is found to exhibit an inhomogeneous structure from the standpoint of droplet size, velocity, number density and volume flux.

1. INTRODUCTION

Pressure atomized sprays continue to be widely employed in a variety of combustion and non-combustion process applications. Despite the widespread usage as well as the comparative ease with which liquid is atomized, the precise mechanism leading to the formation of a spray of droplets is exceedingly complex and poorly understood. As a result atomization research has, to date, largely been confined to dilute sprays operating in easily probed laboratory conditions. Composition of the spray of droplets emerging from industrial nozzles as well as its subsequent interaction with the system's operational environment is far from adequately understood. Limitations of the available diagnostic techniques have been the main impediment in regard to such fundamental studies. Recent advances in non-invasive laser diagnostics is now beginning to offer the prospect of obtaining useful experimental information under realistic conditions concerning near-field spray/droplet performance characteristics. This in turn should help the current efforts relating to the development and verification of spray computational codes as well as improvements in fuel injector technology.

Phase Doppler Anemometry (PDA) is a popular choice for point-wise, simultaneous measurement of size, velocity and number density of droplets in a spray. Laser Sheet Illumination (LSI) is also gaining in popularity for visualising flow-field structures and trajectories in two-phase flow situations. Currently both these techniques are the subject of further developments to enhance their capability and applicability. This is especially true of laser based droplet sizing techniques due to their inherent inability to discriminate between spherical and non-spherical, irregularly shaped particles. Also, comprehensive detailed mapping of a spray using PDA will require a vast number of measurements - thus consuming large amounts of testing resource. Two-dimensional imaging using LSI, in contrast, offers the prospect of rapid, full-field data acquisition. LSI technique can complement PDA measurements by identifying not only spray zones that are worthy of detailed probing but also their inter-relationship. Imaging techniques can also be useful in developing a conceptual model of the various near-field spray-droplet processes eg liquid sheet break up, droplet-droplet agglomeration, droplet-gas interactions causing droplet migration to low pressure regions and the onset of droplet recirculation, etc.

The work reported here is a part of an on-going effort into spray

atomization research at the laboratories of the School of Mechanical Engineering, Cranfield Institute of Technology. Some of the earlier papers have focussed attention upon the performance of airblast atomized sprays [1, 2] whilst this one deals with the application of PDA and LSI techniques to an examination of the structure of a kerosine spray emerging from a simplex pressure atomizer under sea-level pressure and temperature conditions. It should be pointed out, however, that the bulk of the data reported here was obtained during the course of an investigation into the effect of fuel additives on gas turbine fuel injector performance. As a consequence the study was structured to examine the spray performance effects in a broad sense.

2. EXPERIMENTAL DETAILS

A typical gas turbine starter jet was selected for this study. Such atomizers are used to enhance the ignition performance of combustion systems employing a variety of different fuel injector types. They deliver a conical, high-velocity fuel sheet into a relatively low-velocity gaseous environment. In general, the higher the fuel sheet velocity (and hence fuel pressure energy), the finer the resulting droplet spray. The injector was tested to reveal a flow number, FN, of 0.3 GPH/ $\sqrt{\text{psi}}$ using F-35 (aviation kerosine) fuel with an absolute viscosity, η , of 0.0013 Ns/m^2 , surface tension, σ , of 0.027 N/m and density, ρ , of 784 Kg/m^3 . A fuel pressure drop (ΔP_f) of 100 psi was maintained across the injector for the results presented in this paper.

A single-velocity component PDA instrument marketed by Aerometrics, Inc. USA was used in this study. This instrument is an extension of laser Doppler anemometry (LDA) and features three detectors located behind a common aperture of small size - see fig 1 and reference 3 for more details. Use of multiple detectors enables the measurement of the spatial frequency of the scattered interference fringe pattern produced by the passage of a droplet through the beam cross-over region. The detectors produce a Doppler burst signal that is similar but it features a phase difference between them. The droplet velocity information is obtained as in a conventional LDA set up whereas the drops size information is obtained from phase shift measurements. The use of a rotating diffraction grating enables the imposition of frequency shift thus allowing distinction between negative and positive droplet velocities. The instrument is fitted with a counter processor and is interfaced to an IBM PC/AT computer. The individual droplet data is subjected to a sequence of checks before being accepted as a valid sample. Validated droplet size, velocity histograms together with reason for droplets rejected are displayed on the monitor. The shape of particles being measured has to be spherical or near spherical as the instrument works on light scattering principle.

The main imaging diagnostic employed herein comprised a high-intensity, pulsed laser sheet illumination technique. Cylindrical illumination from a Q-switched, frequency doubled, Nd : YAG laser was transformed into a thin sheet through the use of conventional optics as shown in figure 2. The intensity and duration of the pulsed illumination is of critical importance from the view point of spray droplet image quality. A pulse of sufficiently high intensity is desirable in order to penetrate dense, near-field spray zones and hence visualize effectively the processes prevailing in and around the core regions. The duration of the pulse needs to be small enough to "freeze" the fluid motion and hence yield a blur-free image. The laser used in the study was capable of providing a pulse of upto 100 mJ energy with 15 nanosecond duration. The beam emerging from the laser is in the form of a collimated cylinder of about 6mm diameter and this is transformed into a circa 1.5mm thick sheet using the cylindrical lens arrangement. The actual sheet obtained was converging-diverging in thickness and the optics were arranged in such a way as to ensure that the centre of injector

coincided with the waist section of the sheet. A Hasselblad camera with 400 ASA black and white, Ilford X P2, film was used to capture the spray images and was located in a plane orthogonal to the sheet.

To enable a comparison between the performance of LSI technique and conventional high speed photography, a commercially available, argon gas stabilised, spark unit featuring a pulse duration of about 500 nanosecond was also employed in the study. The 16 joule discharge energy unit was configured to deliver cylindrical illumination for in-line imaging using the same camera-film set up as for LSI imaging.

The schematic of the fuel spray rig is shown in figure 3. The spray emanating from the injector was arranged to be horizontal and was directed into a spray collector for disposal. The collection system comprised a cyclone separator driven by a low pressure fan.

The spray drop sizing and visualizing equipment was supported on a 3-D traversable base. The two sets of equipment were such that they could not be supported and used simultaneously. The laser transmitter and receiver were arranged in the forward scatter mode for drop size determination with the measurement probe volume aligned with the centre of the injector.

3. RESULTS AND DISCUSSION

A typical print out from the Aerometrics single-velocity component instrument comprises droplet size and velocity histograms together with information on large number of other spray characteristics including the size-velocity correlation. However information is presented only on those characteristics that are of immediate interest eg RMS - droplet mean velocity, SMD, area and volume mean diameters, number density and, volume flux.

Figure 4 illustrates the variation in Sauter Mean Diameter (SMD) and droplet mean velocity along a horizontal cross-section located at an axially-downstream distance, Z , of 40mm along the spray axis for a fuel pressure drop of 100 psid. The outer edges of the spray appear to contain relatively large, somewhat faster moving droplets whereas the inner regions feature somewhat slower moving, smaller droplets. The apparent assymetry of the two halves of the spray needs some further investigation in order to discount the variable effect of intensity attenuation encountered by the incident and scattered laser beams along their path length. An examination of the size-velocity correlation for velocity spread reveals the absence of droplets featuring negative velocities-impling no recirculatory motion along the measurement diameter.

Area and volume mean diameter variation along the spray cross-section for the same test conditions is depicted in figure 5. The pattern of variation here is much the same as for SMD in figure 4 ie the presence of larger droplets at the spray outer edges relative to the inner regions as well as the assymetry between the two halves.

Figure 6 shows the droplet number density and volume flux data and large spatial variations are evident in both the cases. The centre of the spray seems to contain a high concentration of small droplets which together account for small percentage of fuel by volume. The reverse seems to be the case near the spray outer edges. Some caution here may be necessary as the instrument used in this study was a single-component type set up for measuring axial velocities and consequently may not be detecting droplets with predominantly tangential/radial velocities. Overall the signal quality throughout these measurements was good with the droplet rejection rate peaking at 6%. It would have been interesting to integrate the point-wise volume flux measurements for comparison with actual injected fuel flow rate to

ascertain the credibility of the experimental data but this is hindered by the lack of measurements right upto the very edge of the spray. Unfortunately the peak volume flux region for the negative radial position side of the spray appears to have been missed out.

Figure 7(a) shows the image of the spray using conventional still photography featuring 1/125 sec exposure time while the image captured by using 500 nanosecond spark unit is illustrated in figure 7(b). The time-average image reveals the overall spray cone angle-bulk trajectory while the instantaneous image provides some insight into the break up mechanism.

Spray visualization data obtained using laser imaging is depicted in figure 8. A horizontal cross-section through the centre of the spray cone reveals more details of the break up mechanism relative to figure 7(b) featuring high speed spark photography. The significant improvement in image quality achieved through the application of LSI affords more insight into the nature of disturbances on the fuel surface, the break up length, droplet concentration variations etc. Figures 8(a) to 8(d) illustrate the evolution of the spray structure by capturing vertical views along the spray axis for 5 to 30mm downstream distances. Quite obviously the spray has a solid character to it and the droplet concentration can be seen to change with downstream distance. Use of thinner vertical and horizontal sheets in conjunction with image magnification optics should provide a significant improvement in our understanding of the detailed spray structure-droplet processes in the near-field regions.

4. CONCLUDING REMARKS

The combination of phase Doppler anemometry and pulsed, laser sheet imaging for interrogating spray structure has proved to be satisfactory. The complementary nature of the two techniques should help to minimise the uncertainties associated with atomization studies in general but especially in respect of the denser, near-field spray regions. Further work, however, is needed to enhance their capabilities for more demanding spray studies.

5. ACKNOWLEDGEMENTS

Some of the data reported herein was obtained as a part of a MoD-PE supported study into the Effect of Pipeline Drag Reducing Additive on Gas Turbine Fuel Injector Performance with Rolls Royce plc providing the fuel injectors and technical advice. The authors gratefully acknowledge this support as well as the help of Mr D Whittington, Mr R Fry and Miss B Wilson in making this paper possible.

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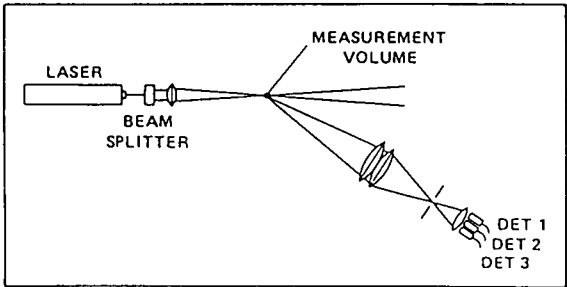


FIG. 1 SCHEMATIC OF PHASE DOPPLER ANALYSER

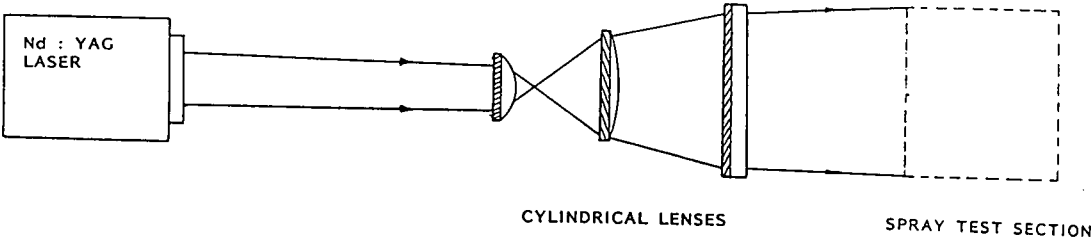


FIG. 2 SCHEMATIC OF SPRAY SHEET VISUALIZATION SET UP

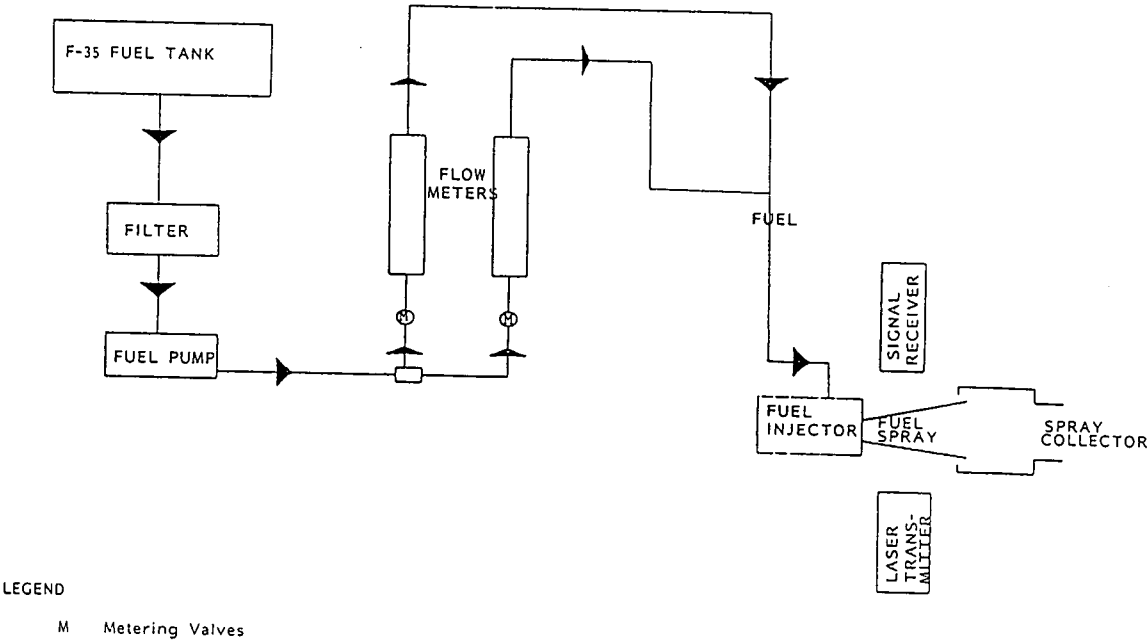
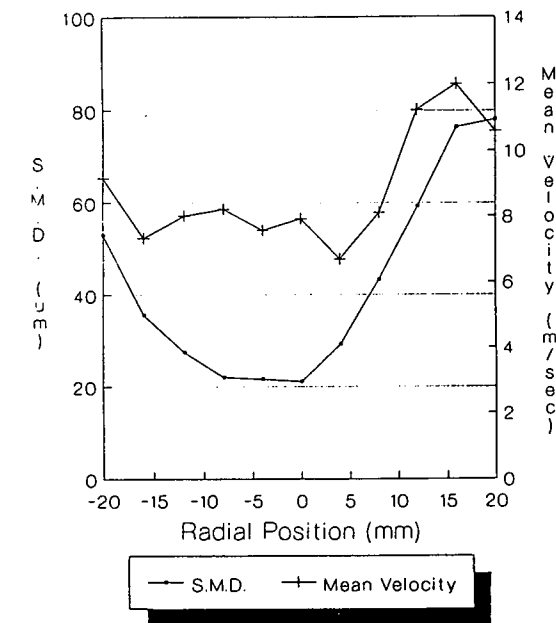


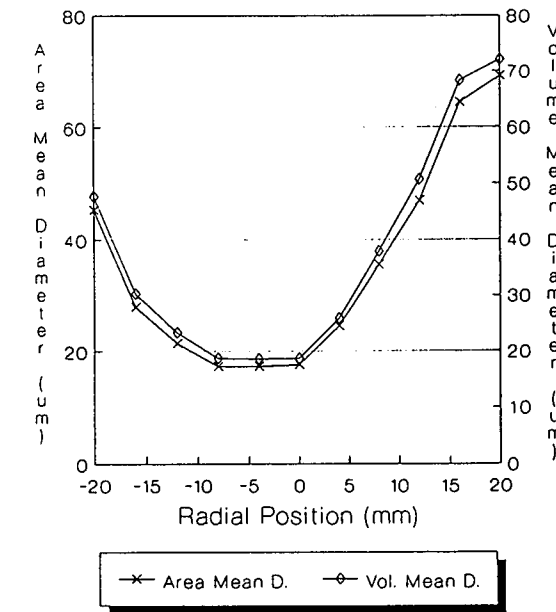
FIG 3 FUEL SPRAY RIG SET UP

Fig.4 Drop Size and Velocity Distribution
Z=40mm, $\Delta P_f=100\text{psid}$



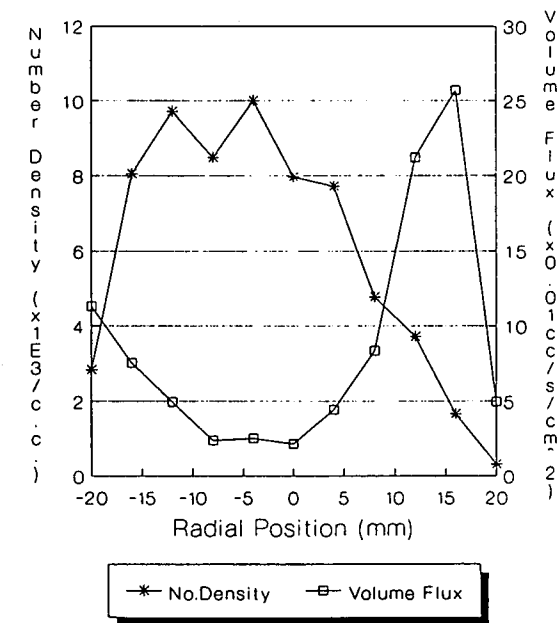
Fuel-F35

Fig.5 Mean Drop Size Distribution
Z=40mm, $\Delta P_f=100\text{psid}$

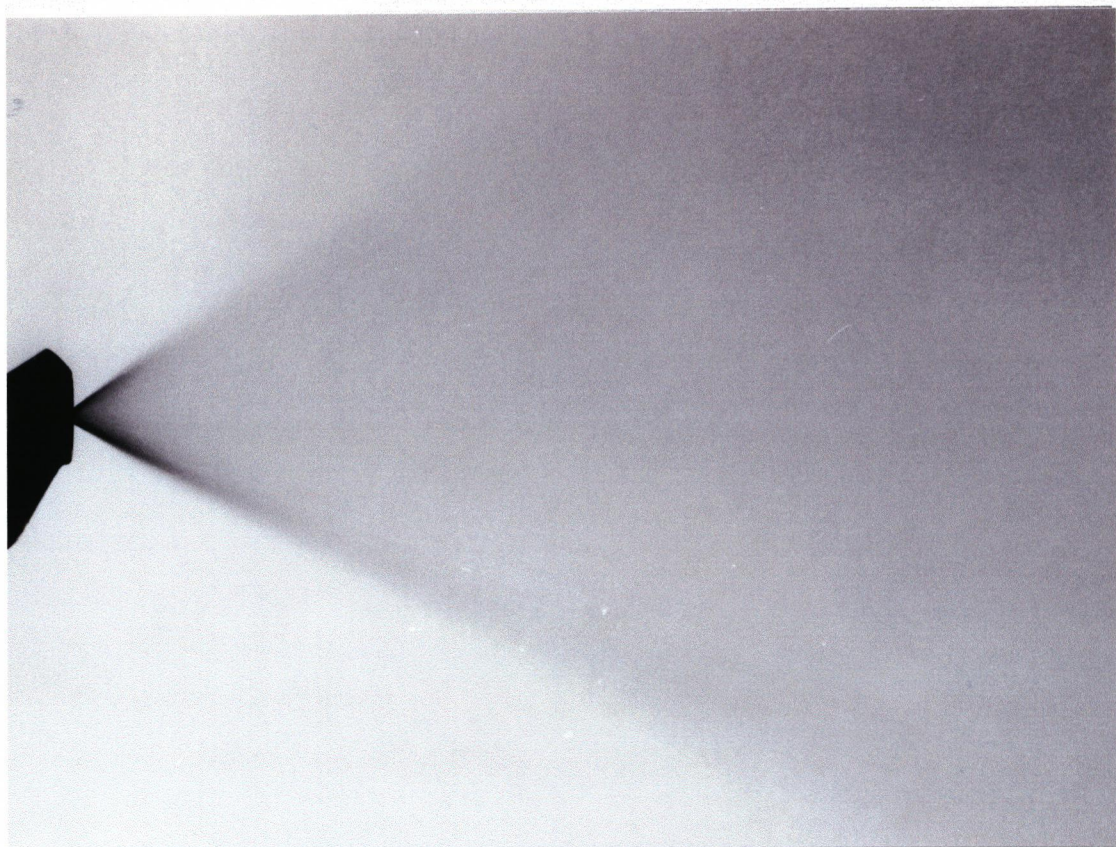


Fuel-F35

Fig.6 Concentration Distribution
Z=40mm, $\Delta P_f=100\text{psid}$



Fuel-F35



(a) Conventional Still Photography



(b) High Speed Spark Photography

FIG. 7 PRESSURE SWIRL ATOMISED SPRAY VISUALISATION



HORIZONTAL VIEW THROUGH SPRAY CONE CENTRE



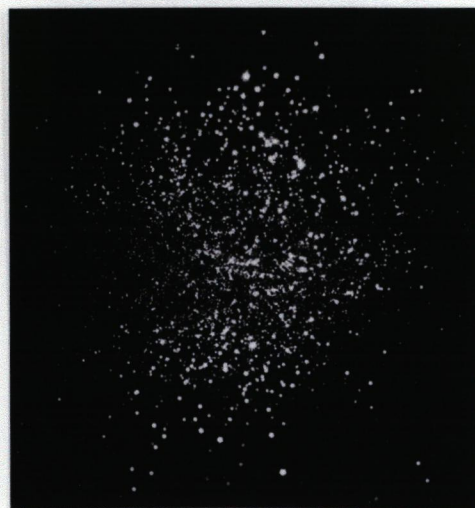
(a)



(b)



(c)



(d)

VERTICAL VIEWS ALONG SPRAY AXIS AT 5 (a), 10 (b), 20 (c) & 30mm(d)
FROM INJECTOR OUTLET

Fig.8 APPLICATION OF LSI TO PRESSURE SWIRL ATOMISED SPRAY VISUALISATION

INFLUENCE OF AMBIENT PRESSURE ON DROP-SIZE AND VELOCITY DISTRIBUTIONS IN DENSE SPRAYS

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The primary aim of the research is to determine the capabilities of modern noninvasive diagnostics for characterising the sprays produced by a practical gas turbine atomizer when operating at realistic engine conditions of pressure, fuel type, and fuel-air throughput. A single-velocity-component Phase Doppler Particle Analyzer is used to measure local variations of drop-size distributions and drop velocities along three spray radii at downstream distances from the atomizer of 50 and 70 mm. In the 50-mm plane, excessive signal rejection rates limit measurements to a maximum air pressure of 9 bar and a maximum kerosene flow rate of 18.6 g/s. At the 70-mm measurement plane, satisfactory results are obtained at air pressures up to 12 bar and fuel-flow rates up to 24.8 g/s. The results show that increases in ambient air pressure lead to larger mean drop sizes and lower mean drop velocities in the spray. This is attributed to the fact that the beneficial effect of an increase in air pressure in raising Weber number is more than offset by several adverse factors, all of which are related to the increase in fuel-flow rate that accompanies an increase in air pressure at constant fuel/air ratio.

Introduction

Prefilming airblast atomizers are widely used in both aircraft and industrial gas turbine combustors. Satisfactory fuel-air mixture preparation is widely accepted as being crucial to optimum gas turbine combustion performance. Most of the previous researches on prefilming airblast atomization have employed specially designed atomizers featuring nonswirling atomizing air. The use of nonswirling air facilitates experimental research, but the results obtained have only limited practical interest because most of the airblast atomizers used in modern gas turbines employ swirling air streams to atomize and disperse the fuel.

Previous studies on practical airblast atomizers featuring swirling air streams (Refs. 1 and 2, for example) have provided useful insights into drop-size distributions and spray/flow field interactions, but in all cases, either the ambient air pressure or the liquid flow rate have been appreciably lower than the values associated with engine operation at high power conditions. The objective of the present work is to remedy this deficiency by attempting spatially resolved droplet size and velocity measurements in the dense sprays produced by swirling air streams at high pressures and high fuel throughputs.

Experimental

The main component of the spray facility is a large cylindrical test vessel designed to operate at high internal pressures. A flexible optical window arrangement permits the use of a variety of laser-based diagnostics. A multistage screw compressor is used to supply the high-pressure air needed to pressurise the test vessel and also to deliver air to the fuel injector, which is located at one end of the pressure vessel and is arranged to spray horizontally along its major axis, as shown schematically in Fig. 1. A rotameter/turbine flowmeter combination is used to measure the fuel-flow rates delivered to the fuel injector. The rotameter handles flow rates up to 68 kg/h, while the pelton wheel flowmeter covers flow rates between 45 and 408 kg/h.

Atomizer:

The fuel injector is essentially a prefilming airblast atomizer, designed by SNECMA and shown schematically in Fig. 2. Low-velocity fuel is first spread into a thin, circumferentially uniform sheet on an annular surface and is then sandwiched between two high-velocity swirling air streams. This configuration promotes a high shearing action between the fuel and the atomizing air and also ensures that the resulting spray is well matched to the combustor airflow pattern. The cone angle of the fuel spray is determined by a complex interaction between the swirling

*Visiting Professor.

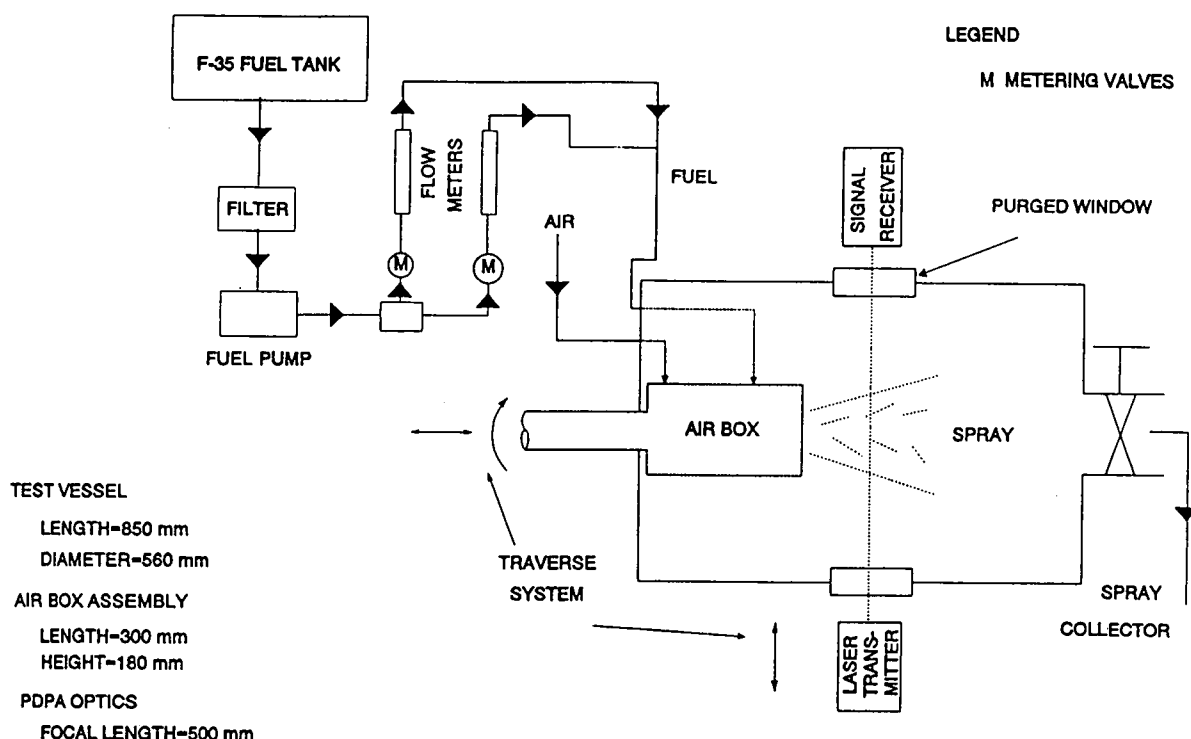


FIG. 1. High-pressure spray facility.

atomizing air streams and the air flow through the liner cup holes shown in Fig. 2. The fuel injector is fitted into a high-pressure airbox that is located inside the test vessel, as shown in Fig. 1.

Two separate and independent traverse systems for the high-pressure spray rig are provided. The traverse system for the laser diagnostics is a mechanical one providing three degrees of freedom. Normally, the optical system moves along the horizontal diameter of the pressure vessel. The repeatability of positioning in this direction is within 0.25 mm. The second traverse system provides two degrees of freedom for the airbox relative to the diagnostics line of sight. The first one is a linear movement along the longitudinal axis of the pressure vessel, while the second is a rotational movement around the axis of the airbox. As both of these movements are controlled by a computer-operated stepper motor, very precise and repeatable injector positioning and repeatability of position can be achieved.

Spray Diagnostics:

Four optical-quality quartz windows provide the desired optical access into the pressure vessel. Each of these large windows has a multipoint purge feed of high-velocity air to prevent the deposition of fuel on the windows. A single-component Phase Doppler Particle Analyzer (PDPA) featuring a 10-mW He-Ne laser, manufactured by Aerometrics Inc., was used in this study. It is described as a single-component sys-

tem because it measures just one component of particle velocity, in this case the velocity component along the main axis of the cylindrical test vessel, which also coincides with the main axis of the conical spray. The theoretical principles on which the PDPA is based have been described by Bachalo and Houser [3]. The instrument was operated in the forward-scatter mode, this being the most favourable orientation for dense spray measurements. During the course of the investigation, special attention was paid to the setting up and operation of the PDPA. The voltage supplied to the photomultiplier tube (PMT) can have a significant effect on the measurements. If the voltage is set too high, signals from the large drops will saturate the PMTs, resulting in a rejection of those signals; thus, the measurement will be biased in favour of the smaller drops in the spray. On the other hand, if the voltage is set too low, signals from small drops will not be detected at all, and the measurements will then be biased in favour of larger drops. Thus, the operator must try several voltage settings in order to identify a range over which the mean drop sizes change only slightly with changing PMT voltage. For these experiments, the PMT voltage was chosen for a given data set to give the lowest overall rejection rate but was then kept constant for all the measurements along the radius. The actual PMT voltage settings employed were 320 V at 1 bar, 380 V at 4 bar, and 420 V at 9 and 12 bar.

The probe volume dimensions were kept fairly

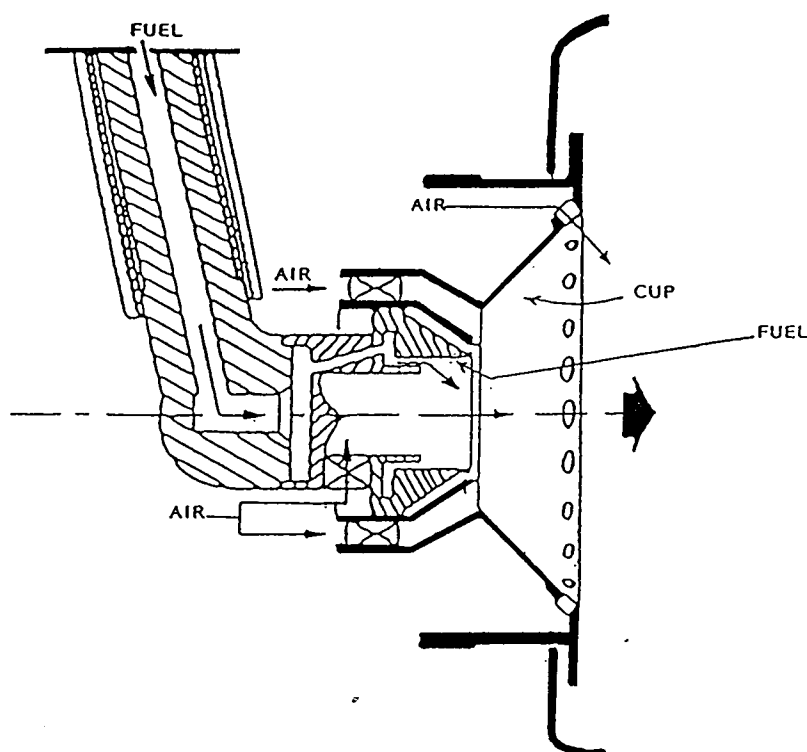


FIG. 2. Fuel injector.

constant by operating on the most favourable track setting with due regard to the problem of particle coincidence in dense droplet regions. In a few instances, this resulted in somewhat higher droplet rejection rates. For a given track setting, the maximum permissible diameter range was used to avoid artificially biasing the data. In contrast, the velocity offset settings were changed as necessitated by observations such as, for example, the presence of negative or near-negative droplet velocities.

Over the entire range of air pressures from 1 to 12 bar, the degree of laser-beam steering encountered as a result of refractive index gradients was judged to be insignificant. The realignment of optics at high pressures was found to be only of marginal benefit to the signal quality, which is consistent with the findings of Drennan et al. [2]. Attenuation of the laser beams was observed to increase with increases in fuel throughput and with decreases in the downstream distance of the measurement plane. This deterioration in electrical signal-to-background noise ratio can be observed on the oscilloscope and leads to high data rejection rates. As the characteristics of the scattered light reaching the receiver are very dependent on the ratio of beam intensity to spray density, clearly a more powerful laser would enhance the dense spray measurement capability of the PDPA.

Test Conditions:

The test conditions were selected to simulate those encountered in gas turbines. The measurements

were taken with a pressure drop across the atomizer, $\Delta P/P$, of 5%, at fuel/air ratios of 0.1 and 0.2. The ambient air pressures employed were 1, 4, 9, and 12 bar. Aviation kerosine ($\mu = 0.0013$ kg/ms, $\sigma = 0.0277$ kg/s², $\rho = 784$ kg/m³—all at 15 °C) was used throughout the test programme. Data were taken at downstream distances from the atomizer face of 50 and 70 mm along radii perpendicular to the spray axis for angular positions of 0°, +90°, and -90° relative to a vertical line drawn through the spray axis. Detailed measurements were made at radial increments of 2 mm for spray radii between 12 and 30 mm, but increments of 4 mm were used for radial positions between 0 and 12 mm, and 30 to 38 mm. Because of the long run times incurred, the radial increment was kept constant at 4 mm for tests at 12 bar. Five thousand droplet samples were taken at each measurement point for all test conditions, except for a few selected positions at 12 bar where the sample size was restricted to around 2000 drops to avoid long run times.

Results

A typical output from the Aerometrics instrument comprises droplet-size and velocity histograms together with the size-velocity correlation. From such curves can be extracted information on variations in drop-size distributions and drop velocities with changes in atomizer operating conditions. Figures 3 and 4 illustrate the results of detailed spray measure-

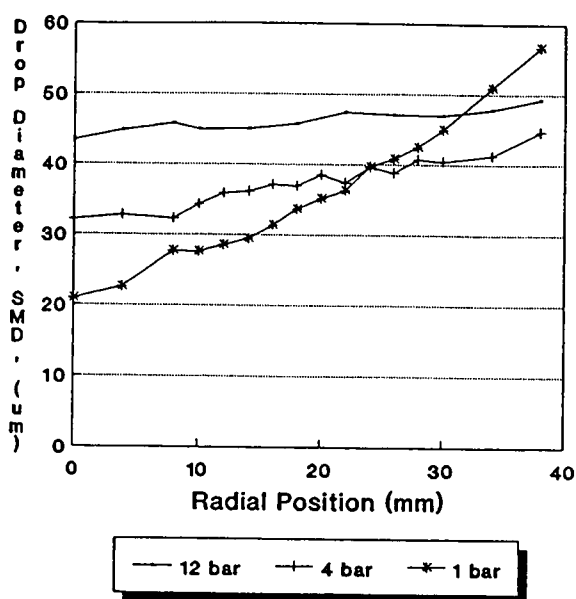


FIG. 3. Variation in SMD with radial position in spray. Fuel/air ratio (FAR) = 0.1.

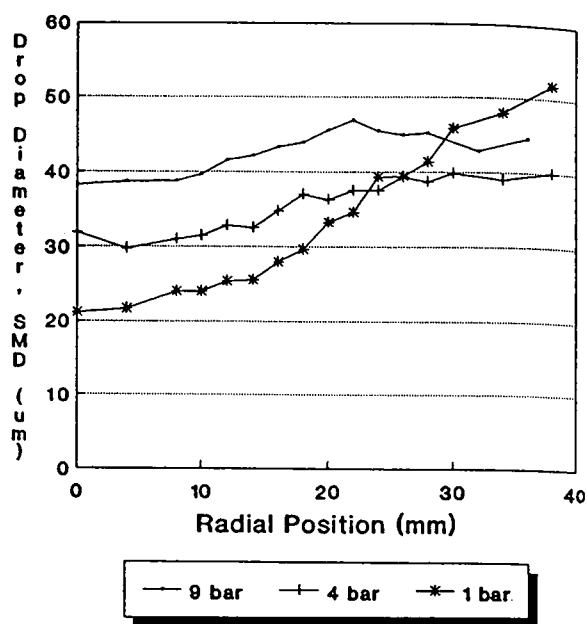


FIG. 5. Variation in SMD with radial position in spray. FAR = 0.1.

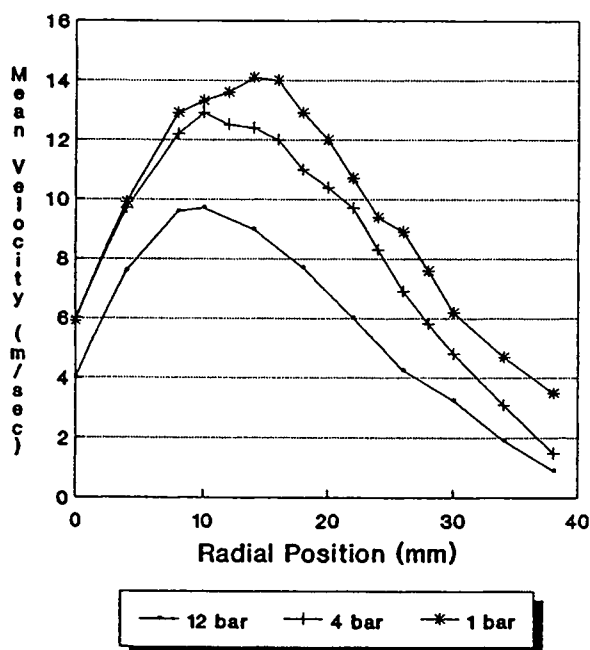


FIG. 4. Drop mean velocity distributions for FAR = 0.1.

ments carried out at air pressures, P_A , of 1, 4, and 12 bar. The atomizer pressure drop, $\Delta P/P$, is 0.05, and the fuel/air ratio is 0.1, corresponding to an actual fuel flow of 24.8 g/s at the highest air pressure. The axial distance of the measurement plane downstream of the atomizer, z , is 70 mm. Radial positions of 0 and 38 mm correspond to the axis and outer edge of the spray, respectively. Figure 3 indicates an increase in Sauter mean diameter (SMD) along the spray ra-

dius at a given air pressure. This increase in SMD diminishes with increase in P_A . For example, the variation in SMD along the spray radius at 1, 4, and 12 bar is 35, 12 and 5 μm , respectively. These data show that the distribution of drop sizes within the spray becomes more uniform with increase in P_A . The effect of variation in P_A on SMD shows no clear trend, but in most regions of the spray, the SMD increases with increase in P_A . Figure 4 shows droplet mean velocity data for the same conditions. As the instrument used was a single-component type, only axial velocity information was obtained. In this figure, the mean velocity is observed to diminish with increase in air pressure. Both the centre and the outer edge of the spray are characterised by relatively low mean droplet velocities.

Figure 5 shows similar data to Fig. 3 for a downstream distance of 50 mm. In these experiments, the air pressure was limited to 9 bar and the fuel flow rate to 18.6 g/s. Comparison between the two figures reveals little effect of downstream distance on SMD, which suggests that atomization is complete within 50 mm of the fuel injector. The corresponding velocity data (not shown) follow exactly the same trends as the data shown in Fig. 4 for the longer downstream distance, except that the mean velocities measured at the spray axis are lower at the highest levels of P_A . A negative velocity was recorded at the spray axis for an air pressure of 9 bar, which suggests the existence of a recirculatory droplet pattern in the inner regions of the spray.

Spray measurements at higher fuel-flow rates, corresponding to a fuel/air ratio of 0.2, were confined to 1- and 4-bar air pressures because the signal quality

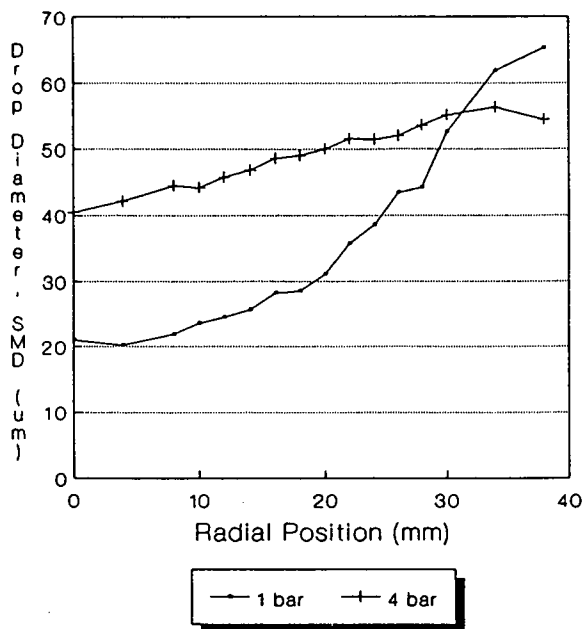


FIG. 6. Variation in SMD with radial position in spray. FAR = 0.2.

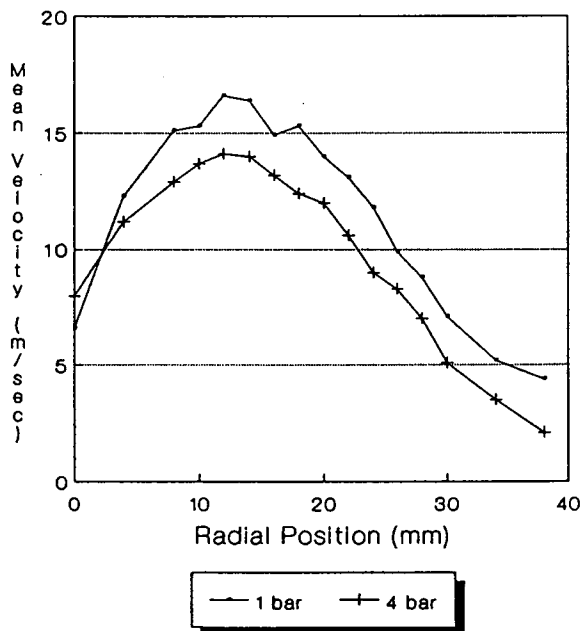


FIG. 7. Drop mean velocity distributions for FAR = 0.2.

deteriorated at higher levels of P_A . The data obtained for $z = 70$ mm are presented in Figs. 6 and 7. If Fig. 6 is examined alongside Fig. 3, there appears to be little difference in SMD at 1 bar, but SMD values are appreciably higher at 4 bar for the higher fuel-flow rates shown in Fig. 6. The droplet mean velocity distributions shown in Figs. 4 and 7 for the two different fuel throughputs exhibit only small differences in absolute values at any given level of air pressure.

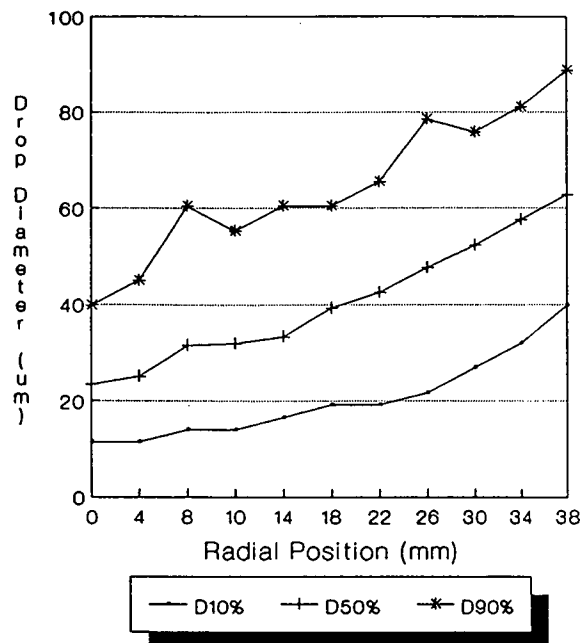


FIG. 8. Drop size distributions for $P_A = 1$ bar and FAR = 0.1.

Examination of the data presented in Figs. 3, 5, and 6 reveals some interesting and unexpected results. Throughout most of the spray region, an increase in pressure leads to an increase in mean drop size. This contradicts what one might anticipate intuitively since an increase in air density would be expected to intensify the aerodynamic shear forces causing liquid disintegration. Only in the outer, more dilute regions of the spray does the spray exhibit the customary decline in SMD with increase in air pressure. Unfortunately, there are no comparable studies available in the open literature that feature PDPA measurements at high air pressures on the type of atomizer employed in this investigation. Moreover, no information is available on the manner and extent to which changes in air pressure affect the cone angle of the spray.

In an attempt to shed more light on this issue, it was decided to examine the behaviour of different drop-size classes in addition to SMD. Three drop-size classes corresponding to 10, 50, and 90% cumulative volume points, i.e., D_{10} , D_{50} , and D_{90} , were selected. Not surprisingly, the D_{50} data conform closely to the SMD [4]. As illustrated in Figs. 8 and 9 for air pressures of 1 and 12 bar, respectively, the different diameter classes exhibit fairly similar behaviour across the spray radius. The mean axial velocities corresponding to the three different size classes are plotted in Figs. 10 and 11 for the two extreme levels of pressure. These figures show that, at the higher air pressure, the three drop-size classes possess practically the same mean axial velocity, while, at the lower pressure, there is a noticeable difference

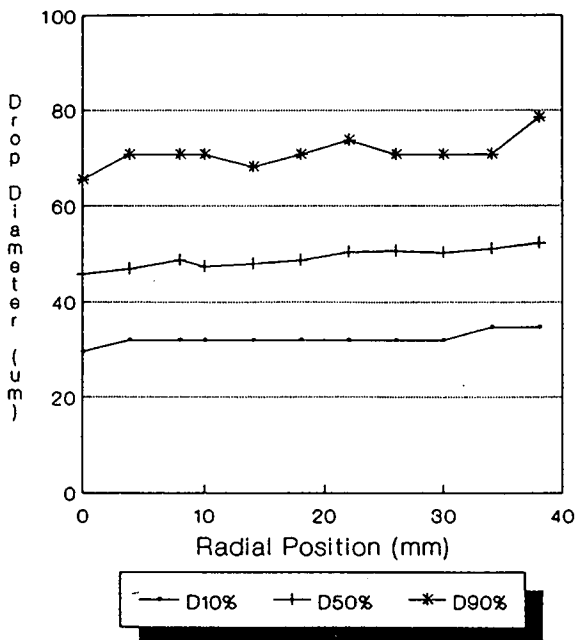


FIG. 9. Drop size distributions for $P_A = 12$ bar and FAR = 0.1.

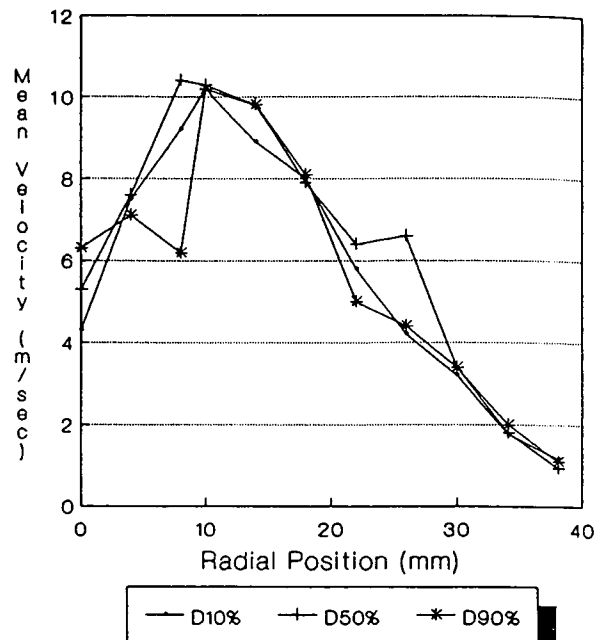


FIG. 11. Drop mean velocity distributions for $P_A = 12$ bar and FAR = 0.1.

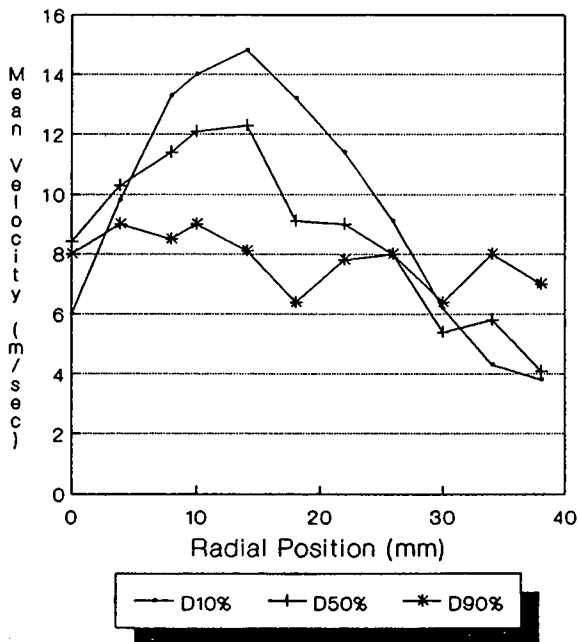


FIG. 10. Drop mean velocity distributions for $P_A = 1$ bar and FAR = 0.1.

in the mean velocities in the inner spray regions. This difference in droplet velocity at low air pressures is attributed to the influence of air pressure on the aerodynamic force ($0.5 \rho_A U_A^2$) experienced by a droplet in a flowing air stream. At high pressures, this force is large enough to accelerate all the droplets up to a common velocity, regardless of size. At low pres-

ures, however, where aerodynamic forces are appreciably lower, only the smallest droplets in the spray can attain a velocity close to that of the atomizing air stream. The larger drops lag behind the smaller drops to an extent that depends on their size, as shown in Fig. 10.

Figure 12 shows the effect of air pressure on the radial distribution of D_{90} within the spray. At all pressures, D_{90} is seen to increase with increase in spray radius. This same effect was also observed for the other drop-size classes, D_{10} and D_{50} . Measurements on the effect of air pressure on the mean axial velocities corresponding to a given size class revealed low mean velocities (1–2 m/s) near the outer edge of the spray at high pressures. Experiments carried out at 9 bar revealed negative velocities, which implies the existence of a recirculatory airflow pattern. It is conceivable, therefore, that the existence in close proximity of low-velocity negative and positive flows could give rise to droplet coalescence, which could account for the observed large drop sizes at higher air pressures. It is also possible that, at high pressures, some of the smallest droplets are passing by undetected, the light scattered by them being lost in the general background noise, which increases with pressure. However, a large number of small droplets would have to be missed out for the effect to be significant since SMD is more strongly influenced by the larger drops in the spray.

Another possible explanation for the observed increase in droplet diameter with air pressure is the reduction in relative velocity between the fuel and

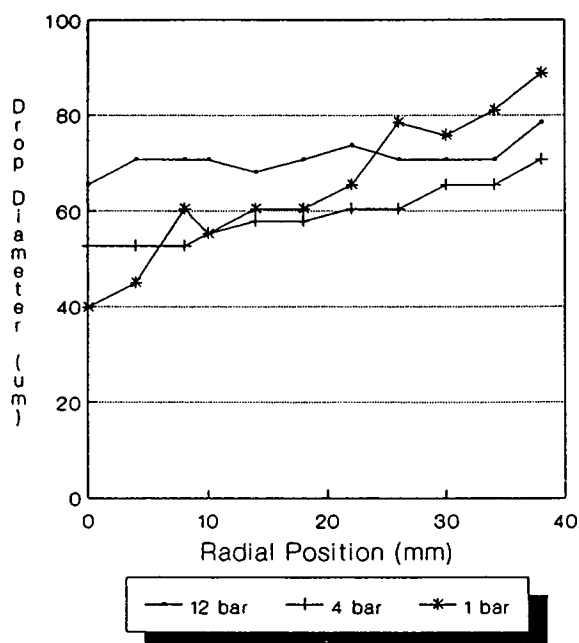


FIG. 12. Variation of D_{90} with radial position in spray. FAR = 0.1.

the atomizing air that accompanies an increase in P_A . The atomizing air velocity remains constant regardless of variations in P_A because the atomizer operates at a constant value of $\Delta P/P$. However, for a constant fuel/air ratio, and assuming the fuel-film thickness at the atomizing edge remains constant, the fuel velocity is directly proportional to the fuel-flow rate which, in turn, is proportional to P_A . Thus, an increase in air pressure must inevitably be accompanied by a reduction in relative velocity. It is recognized that the fuel-film thickness may not be independent of fuel-flow rate and, in fact, is likely to increase with increase in fuel-flow rate. This would diminish the force of the relative velocity argument, but if the fuel-film thickness does increase with fuel-flow rate, this would also impair atomization since it has been established both theoretically and experimentally that mean drop size is proportional to the square root of the initial fuel-film thickness [5,6]. Thus, regardless of whether the influence of an increase in air pressure on atomization quality is manifested via a reduction in relative velocity or an increase in fuel-film thickness or, as is likely, a combination of both these effects, the end result is always to impede atomization and raise the SMD.

Droplet coalescence has been mentioned already as a possible cause of larger drop sizes at high pressures. In these experiments, the fuel/air mass ratio was kept constant regardless of variations in air pressure. Thus, the volumetric fuel/air ratio increased in direct proportion to P_A . This has little practical significance for the spray as a whole, which is always fairly dilute,

but in the initial dense breakup region, an increase in volumetric fuel concentration has two adverse effects on atomization: (1) it provides a greater opportunity for droplet coalescence to occur, and (2) it restricts the interaction between the atomizing air and the fuel. Because, with increase in P_A , a larger proportion of the breakup region is occupied by fuel and, in consequence, a smaller proportion by air, not only is there more fuel to atomize, but the "accessibility" of the fuel to the atomizing air is diminished. By the time the atomizing air has achieved complete access to the fuel, the conditions for sheet and ligament breakup are less favourable. This is believed to be the main reason why drop sizes tend to increase with increase in P_A , despite the higher Weber number.

For this hypothesis to have any substance, an increase in fuel throughput at a constant air pressure should result in a higher SMD. Although the data available for such an assessment are sparse, some confirmation may be obtained by comparing the results presented in Figs. 3 and 6. These data correspond to exactly the same test conditions, except that, in one case (Fig. 6), the fuel-flow rate is twice that of the other (Fig. 3). Examination of these two figures shows that, at 1 bar, the SMD values are largely independent of fuel-flow rate. This is perhaps hardly surprising since, at this low pressure, the fuel-flow rate is always relatively low. However, at a pressure of 4 bar, where the effect of doubling the fuel-flow rate is appreciably higher, comparison of Figs. 3 and 6 shows significantly higher values of SMD for the higher fuel-flow rate.

It is concluded, therefore, that the observed increase in SMD with increase in air pressure is due not to the effect of pressure per se but is caused by the higher fuel-flow rates associated with atomizer operation at high pressures.

Conclusions

From detailed measurements of drop sizes and drop velocities carried out over wide ranges of air/fuel ratio and ambient air pressure on a practical airblast atomizer featuring swirling air flows the following conclusions are drawn.

1. The feasibility of obtaining detailed spray droplet data at an operating pressure of 12 bar and a fuel throughput of 24.8 g/s has been demonstrated using a single-component Phase Doppler Particle Analyzer.
2. Higher fuel throughputs and reductions in measurement plane distance from the atomizer below 70 mm resulted in excessive attenuation of the laser beams before and after the measurement probe volume. This extinction resulted in high data rejection rates. Clearly, a more powerful laser

would alleviate this problem and extend the measurement capability of the PDPA.

3. All the experimental data obtained on the influence of ambient air pressure on mean drop size show that an increase in air pressure above the normal atmospheric value causes the SMD to increase. Although the basic effect of an increase in air pressure is to raise the Weber number and thereby improve atomization, this beneficial effect is more than offset by several adverse effects, all of which are related to the increase in fuel-flow rate that accompanies an increase in air pressure at constant fuel/air ratio. These include increase in initial fuel-film thickness, reduction in relative velocity between fuel and atomizing air, increased droplet coalescence, and lower accessibility of the fuel to the atomizing air.
4. The mean axial velocities of the droplets in the spray diminish with increase in air pressure, which also tends to make droplet velocities more uniform and less dependent on individual drop size. Both these effects are attributed to the influence of air pressure on the aerodynamic forces experienced by droplets in a flowing air stream.

Acknowledgments

The financial support provided for this work by the CEC as part of its "Low Emissions Combustor Technology" BRITE/EURAM programme is gratefully acknowledged. Special thanks are also due to Mr. C. K. Tam of Cranfield University for his painstaking efforts in acquiring the experimental data contained in this paper.

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COMMENTS

A. K. Gupta, *University of Maryland, USA*. I have a clarification, a comment, and a question. Were the tests carried out at 12-atm fuel supply pressure or chamber pressure? Providing SMD data in the spray yields little information on the size and number density distributions of the spray. What are the accuracy and precision of your reported data?

Author's Reply. The droplet measurements were undertaken at chamber air pressures of up to 12 bar. The authors agree with the comment that providing SMD data alone gives little insight with respect to size distributions. For this as well as other reasons outlined in the paper, analysis included D10, D50, and D90 diameters. Number density data were not presented in the paper partly because of to paper length restrictions, but more importantly because the data quality was believed to be unreliable. This was because of the use of a single-velocity component system in a spray field featuring recirculating flow. The level of precision regarding the drop size-velocity measurements using phase Doppler systems has been covered adequately in the published literature.

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Scott A. Drennan, *Coen Company, Inc., USA*. In your experiment, the flow rates of liquid and atomizing air increase as ambient pressure is increased, causing an increase

in the spray density and possibly an increase in the data rejection rate. Please discuss how you feel this increased data rejection rate at higher pressures affects your spray statistics. It is also interesting to note the decreased radial variation in drop size and velocity as the ambient pressure is increased. Do you believe that a collapsing effect on the spray at elevated pressure is causing this decreased radial variation? Were data acquired at axial locations closer to the spray tip to determine how the spray evolves axially? Perhaps the spray at high pressure indicates a size-velocity correlation closer to the spray tip, as seen in the low-pressure spray data, which decays rapidly because of increased ambient air drag forces at high pressure.

Author's Reply. For the entire set of data outlined in the paper, the maximum rejection rates encountered were below 10%. Under these circumstances, we believe the spray statistics did not change significantly with increasing air pressure. We do not have any spray images at high air pressures to identify the change or lack of change in spray cone angle placement. Consequently, we are unable to say whether this may be an influencing factor in the decreased radial variation in drop size and velocity. Spray measurements were made at two axial locations only: 50 and 70 mm from the injector tip. Evolution of the spray at shorter axial distances could not be ascertained due to excessive laser beam attenuation and data rejection rate.

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Development of Planar Laser Sheet Imaging for Spray Diagnostics

Introduction

Commercial optical measurement techniques used in spray and liquid atomization research normally depend on the analysis of light scattered by drops. For example, the Malvern sizer is based on the analysis of narrow angle diffraction patterns in the near forward direction, while the geometrical-optics pattern arising from reflection/refraction of light rays is processed in Phase Doppler Anemometry to generate particle size and velocity information simultaneously. These well developed techniques provide droplet data that is along a line-of-sight or point-wise in nature. Establishing a detailed map of the entire spray flow field may potentially be inaccurate or laborious when using these two diagnostic approaches. Furthermore, only signals from spherical drops in dilute regions can be processed reliably; thus their applications to the near field dense spray are rather limited where non-spherical particles and high drop concentrations tend to dominate the flow field.

Planar laser imaging has the advantage that it generates a map of two-dimensional information and thus is more efficient. Unlike the aforementioned two techniques wherein the measured data are deduced from the detected signal, the signal in planar imaging yields a more direct link to the liquid particles. Planar imaging is not restricted to spherical drops and hence can be applied to the near-field regions of sprays. Flow characteristics such as the liquid status at the nozzle exit, breakup mechanism, ligament formation-disintegration, and drop formation can be visualized. Parameters of spray geometry-structures, for example spray angle, can be obtained from planar images as well.

Early imaging studies often employed comparatively low power light sources, for example, copper vapour and Argon lasers for direct imaging and other low power lasers for holographic experiments (Chigier (1991)). The availability of powerful dye lasers could extend the laser imaging to dense sprays with a more acceptable signal to noise ratio. The high laser power on the other hand may generate strong resonance signals due, for example, to morphology dependent resonance, and image processing may be hampered by such disturbing optical effects. Such non-linear effects on spray diagnostics have been the subject of recent research (Serpengüzel et al. (1992)). One approach when applying high power laser for imaging is to dissolve fluorescent dye

in the liquid and to selectively analyze the wavelength shifted signal due to the fluorescence while rejecting the elastic scattering signal. Droplet sizing using this method has been demonstrated by Coy and Santavica (1991) and Bazile and Stepowski (1994), while Carabell and Farrell (1993) applied a similar technique for air-fuel ratio visualization in a diesel spray.

Whereas much emphasis in the past has been on drop measurement, liquid disintegration and atomization history are receiving more attention, given their role in drop formation. Planar imaging may provide complementary information, especially in the near field of a dense spray where commercial instruments cannot be relied upon. This paper reports the current status of efforts directed at the development and application of a planar laser imaging technique to spray near field zone characterization. Global images of spray flow pattern and prevailing structures, along with further extension of this technique for detailed liquid atomization measurements in relation to liquid breakup process, is outlined.

Experimental Details

Electro-Optics

A pulsed Nd:YAG laser, made by Spectron Laser Systems, was used as the light source. Each pulse was of 15 nanoseconds duration with a maximum output energy of 126 mJ. The green beam (532 nm), excited from the second harmonic of the YAG laser, had a diameter of 6 mm with a divergence angle of 2.0 mrad. This circular beam was transformed by a pair of cylindrical and spherical lenses into a thin sheet with a thickness and width of 0.36 mm and 20 mm, respectively (Figure. 1). The flat laser sheet had an energy density of 119 MW/cm² (or 1.8 J/cm²). The thickness determines the spatial resolution of the interrogation volume, whereas the width can be adjusted, for example, to 10 mm in the present study, to suit the field of view requirement of the image recording medium.

A 35 mm Nikon camera was placed orthogonally to the light sheet to record the laser-visualized section of the flow field. The camera was fitted with a K2 long distance microscope lens made by Infinity Photo-Optical Company. A standard objective lens was combined with the K2 and the numerical aperture at a distance of 500 mm away from the probing plane was 0.037. At this distance, a primary magnification factor of 4.6 (ie. image size on negative-actual object size) was obtained with a 15x eye piece. Ilford XP2, 35 mm black/white negative films of ISO 400 speed were exposed and then push-processed to increase the film sensitivity without loss of image resolution. The images from the negatives were enlarged to yield a total magnification factor of 13.8. These enlarged prints were then scanned by a Canon CLC 10 copier linked to a 486 personal computer for image analysis. The digitized information was stored in the computer with 256 grey scales and maximum 3312x4661 pixels (400 dot-per-inch) of 8 bits. The digital images were thresholded and binarised on a workstation to generate quantitative information and void fraction data are presented here. Void fraction is defined as the percentage of

cross section occupied by air within the total probe volume. When the void fraction approaches unity, the whole volume is occupied by air and no liquid is present. Furthermore, extinction of the planar laser sheet as it passed through the spray jet was measured and the inverse logarithmic ratio of the transmitted laser intensity I and the initial intensity I_0 , $(\ln(I/I_0))^{-1}$, is a measure of the average extinction due to the spray over the 10 mm test length. The extinction can then be correlated to the void fraction measurement.

Sprays

Images of pressure jet and airblast atomized sprays were captured with a global field of view for the purpose of getting qualitative information about the atomization process. Aviation kerosene was dispersed from the atomizers at moderate throughput into a quiescent environment. To retrieve accurate quantitative details from such images, the planar imaging technique needs to be evaluated. A co-axial plan jet airblast atomizer was employed because of its relatively simple-structured flow field and thus its suitability for the diagnostics development. The detailed setup of this compact spray has been described by Zheng and Jasuja (1994) and will therefore be outlined in brief. Water issued at a velocity of 10 m/s from a 0.5 mm bore plain orifice, into a co-flowing air stream. The air flow was confined to a pipe of 62.4 mm inside diameter at a velocity of 67 m/s. The nozzle was located in the centre of a tubular perspex section featuring two slots along the path of the laser sheet. Also provided was a window perpendicular to the laser sheet for capturing the image.

The energy density of the YAG laser beam, which was 119 MW/cm², exceeded the 0.3 MW/cm² threshold level for morphology-dependent resonance - MDR - for drop diameters smaller than 0.2 mm, as suggested by Bazile and Stepowski (1994). In this study featuring water alone as the medium, images of larger dimension spray elements which were illuminated by the high energy density laser showed MDR to be prevailing. To eliminate the effect of this non-linear interference on planar imaging, ionic dye molecules were dissolved in deionised water to generate fluorescence signals at a wavelength range that was shifted from the green incident laser beam. Rhodamine 6G was doped into water at a concentration of 1x10⁻⁴ mole/litre. Higher concentrations absorbed too much laser energy, while lower ones did not generate strong enough fluorescence signals and the MDR was observed to prevail on the negative film. Long pass filters (OG 550) were used to allow the fluorescence signal to pass through while blocking the resonance signal.

Results and Discussion

The spatial resolution of laser imaging is defined by the thickness and width of the laser sheet, the images captured being from a specific region of the illuminated planar slice of spray. Global images depicting structure of the spray formed by practical atomizers at atmospheric pressure and temperature conditions are presented in Figure 2. The pressure jet spray shows a detailed liquid breakup history. The fuel, in this case kerosene, issues as a continuous sheet at the injector exit where the

aerodynamically-induced wave on the surface is clearly recorded. As the kinetic energy of the liquid augments the interaction between the liquid and ambient air, the growth of the liquid oscillation leads eventually to the formation of discrete ligaments and large droplets. The spray angle can be readily inferred from the image (Figure 2 (a)). The image of an airblast atomized efflux at one particular flow condition shows a relatively dilute spray (Figure 2 (b)). The fuel emerging from the nozzle is already in the droplet form, implying the onset of air-liquid mixing inside the injector. The recirculating flow pattern downstream from the exit demonstrates the existence of drop transport within the inner spray regions, due possibly to the prevailing pressure differences. Fuel distribution in the flow field and the droplet flow trajectory are also illustrated in the picture.

Such information may help atomizer designers to improve the air-fuel mixing process in a qualitative sense. However, to obtain detailed quantitative data from such planar images, further tests were conducted, and Figure 3 shows images from three regions along the axis of a co-axial plain jet airblast atomized spray. The three pictures are taken at different times. This type of plain jet atomization has been applied extensively in internal combustion and rocket combustion chambers and can, under certain flow conditions, yield distinct atomizing stages where liquid cylinder (round jet), ligaments and drops prevail. Instead of revealing the solid water jet in the 0-10 mm axial region, the image however appears as a hollow jet where only the front and back interfaces along the propagating path of the incident pump beam are illuminated. The light scattering from the ruffles at the liquid/air interface, produced by random fluctuations, leads to a distorted presentation of the spray structure. Due to the non-absorbing/emissive nature of liquids such as water and kerosene at the wavelength of 532 nm, ionic dye molecules, in this study Rhodamine-6G, have been doped into water for emission enhancement purposes. Images in Figure 4 record the wavelength shifted laser induced fluorescence from R-6G while rejecting the scattering at the incident green wavelength. These planar images have revealed a 'solid' rather than a 'hollow' structure of the jet, especially in the 0-10 mm axial region where a solid liquid jet presence in the probe volume should be expected.

The fluorescence signal levels vary across the field of view. Bazile and Stepowski (1994) found that the fluorescence intensity from the R-6G in methanol is proportional to the mass of dissolved dye in the probe volume when the dye concentration in the liquid is very low (0.02 ppm). The R-6G concentration in water, 1×10^{-4} mole/litre in this experiment, may be one of the factors contributing to the varying intensity profiles across the jet. Physical-optical effects may also be responsible. The latter is a complex issue and only drops of small dimensions (diameter less than 0.2 mm) have been investigated (Coy and Santavica (1991) and Bazile and Stepowski (1994)). The non-uniform intensity distribution in the liquid is not desirable from the viewpoint of image analysis. Data reduction is performed first by thresholding the global image and then by binarization (Nicholls (1994)). The binarised images which contain only two grey levels, i.e. black and white, represent

the liquid jet flow along the spray axis within the probe volume defined by the 0.36 mm thick sheet (Figure 5). These high magnification images exhibit the detailed surface wave growth induced by the co-flowing air turbulence and the eventual breakup in the downstream region. The axial distance at which the air begins to penetrate in towards the centreline of the jet can be obtained from Figure 5 (b) and it is about 12.6 mm or $25.6d_0$, d_0 being the jet initial diameter. Such a long intact length reflects the poor atomization due to the low air velocity, and hence low air turbulence, together with high liquid surface tension.

Void fraction is used here as a measure of air-liquid mixing and the local value can be used as an indicator of dense or dilute spray regions (Faeth (1987) and Carreau et al. (1993)). The base area for void fraction calculation is set to be the same for all three images, i.e. the largest area of Figure 5 (c). The averaged values of void fraction for regions 0-10, 10-20 and 20-30 mm in Figure 5 are plotted in Figure 6 together with the corresponding extinction measurement. The inverse extinction level, which indicates the liquid concentration, and the void fraction increase in a similar manner as the liquid flows downstream and the dispersion develops to yield a dilute spray. A direct correlation of the two parameters may be obtained when both measurements are taken simultaneously. Better spatial resolution should be explored for this correlation by reducing the length of the field of view. This may however need higher image magnification and careful optimization to take account of the spray geometry.

Concluding Remarks

Planar laser sheet imaging has been applied to spray measurements. Global views of the spray structure revealing flow pattern and drop trajectory have been illustrated in both dense near field and dilute regions. Further tests based on laser induced fluorescence by doping deionized water with ionic dye Rhodamine 6G have successfully eliminated the strong elastic scattering interference and plausible information from fluorescence images has been obtained. Void fraction data derived from image processing of the liquid disintegration process are compared with laser beam extinction measurements and similar trends were observed.

Further investigations are needed to clarify the optical-physical interaction between the liquid and the laser beam, for example, the varying fluorescence intensities from the water/R-6G solution. The tentative correlation between void fraction and laser extinction as a means of reliably identifying various spray regimes will be explored over a wide range of conditions.

Acknowledgement

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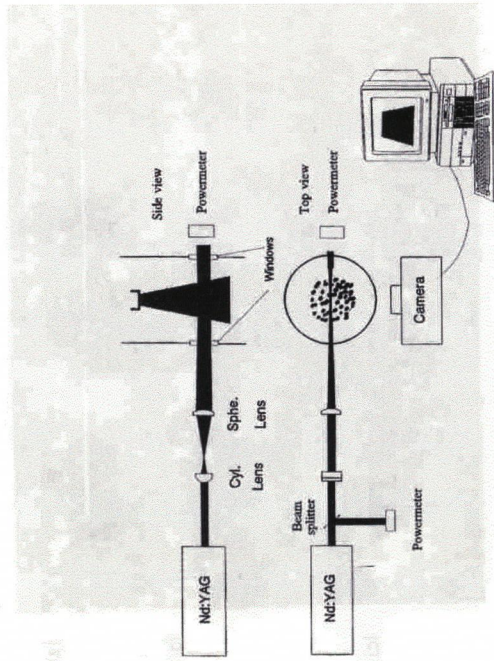


Figure 1 Schematic diagram of laser sheet imaging set up

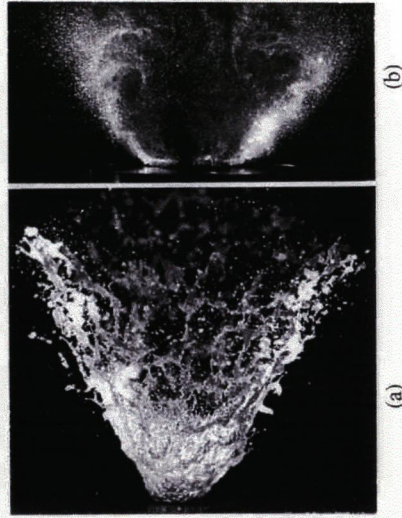


Figure 2 Laser sheet images of (a) pressure jet spray and (b) airblast spray

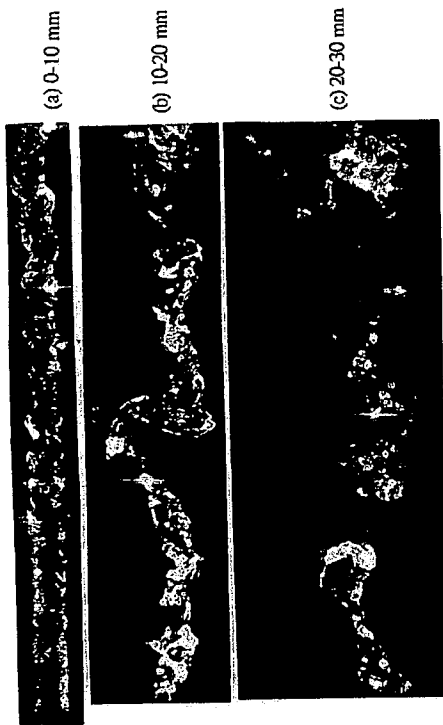


Figure 3 Laser sheet images of co-axial airblast spray at three axial positions

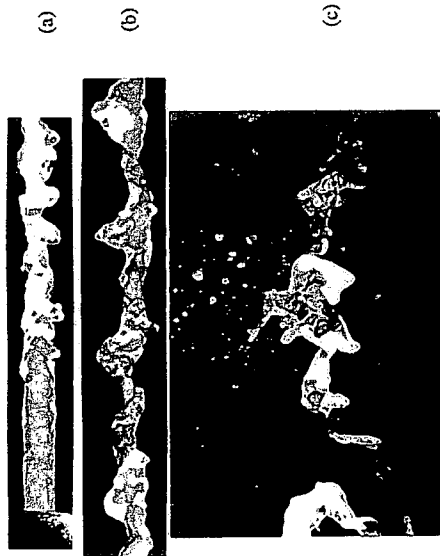


Figure 4 Laser induced fluorescence images of co-axial airblast spray at three axial positions

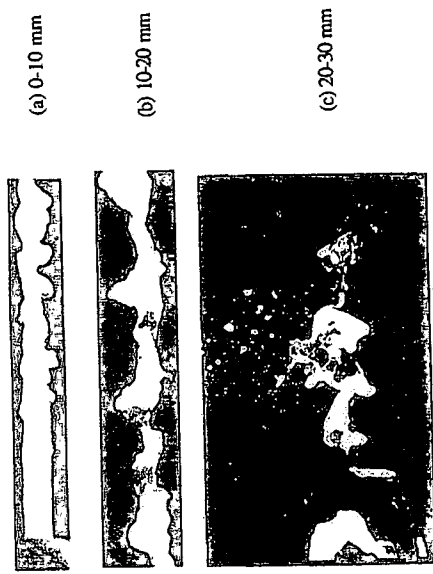


Figure 5 Binarised images of Figure 4.

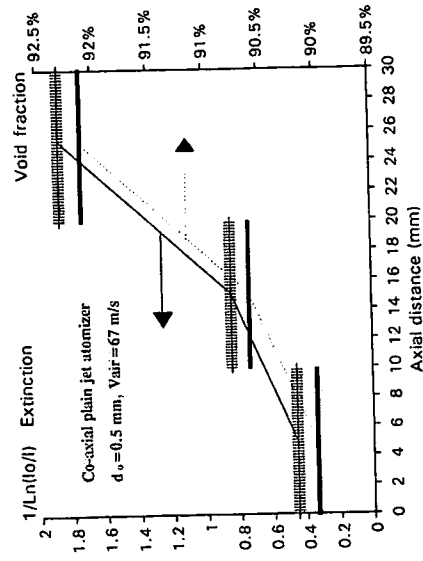


Figure 6. Variation of extinction and void fraction along the spray axis. Measurements are averaged along the axial distance as shown.

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Laser sheet imaging of dense gas turbine sprays

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Synopsis

Detailed structure of dense airblast atomized sprays is explored by applying planar laser imaging techniques under ambient air pressure and temperature conditions. Laser induced fluorescence, LIF, imaging is judged to be a reliable technique for monodisperse drop size measurements from a fundamental standpoint. Laser sheet imaging, including LIF, provides valuable insight into important spray characteristics such as cone angle, prevailing structures and uniformity. It can potentially provide near-field information that is inaccessible when using other existing instruments.

1. Introduction

Commercial optical measurement techniques used in spray and liquid atomization research, such as the laser diffraction based Malvern Sizer and the light scattering interferometry based Phase Doppler Analyzer, provide droplet data that is line-of-sight or point-wise in nature. Their application to dense, near-field spray regions is rather limited where non-spherical particles and high drop concentrations usually dominate the flow-field. Planar laser imaging has the advantage that it provides full-field, two dimensional information and thus is more cost effective. Unlike commercial drop sizing instruments, it is not restricted to spherical drops and hence can be applied to the near-field regions in a spray. Flow characteristics such as liquid status at the nozzle exit, break up mechanism, ligament formation-disintegration and drop

formation can be visualized. Parameters relating to fuel placement, for example cone angle, liquid movement patterns, etc. can also be obtained from planar images.

Early imaging studies often employed light sources with comparatively low power, for example copper vapour and Argon lasers for photographic imaging and other low power lasers for holographic experiments (Chigier (1991)). High fuel concentration within the probing plane poses a constraint for optical imaging because the laser beam energy diminishes as the beam travels through the dense flow-field. However, the availability of powerful dye lasers could extend laser imaging to dense sprays with a more acceptable signal-to-noise ratio. On the other hand high laser power may generate optically induced resonance signals, related for example to the morphology of the particle, and image processing may consequently be hampered by their presence. The effects of these non-linear phenomena on spray diagnostics have been the subject of recent research (Serpengulzel et al. (1992)). When applying high power lasers for imaging one approach is to dissolve a fluorescent dye in the liquid and then selectively analyze the wavelength shifted signal due to fluorescence while rejecting the elastic scattering signal. Droplet sizing based on this broad approach has been demonstrated by Coy and Santavicca (1991) and Bazile and Stepowski (1994), while Carabell and Farrell (1993) and Igushi et al. (1993) applied similar techniques to determine air-fuel ratio and local fuel concentration variation in practical sprays.

This paper reports the current status regarding the development and application of planar laser imaging techniques to the characterization of sprays in the near-field zone. The impact of high spray density on imaging is assessed. Global imaging to yield insight into spray placement and prevailing structures is also investigated. Reliability of determining droplet sizes directly from

the acquired images is evaluated on a monodisperse droplet stream in order to determine its precise capabilities from a fundamental viewpoint. This approach differs from drop sizing methods that are based either on the absolute LIF intensity level as used by Bazile and Stepowski (1994) or on the stimulated Raman scattering spectral analysis as reported by Golombok and Pye (1990).

2. Experimental Details

A pulsed Nd:YAG laser was used as the illuminating source. Each pulse was of 15 nanosecond duration with a maximum output energy of 126 mJ. The green beam (532 nm) excited from the second harmonic of the YAG laser had a diameter of 6 mm and it was transformed by a combination of cylindrical and spherical lenses into a thin sheet. Two types of imaging were evaluated, one for the sizing of monodisperse droplets and the other for global spray pattern characterization. A 8 bit CCD camera was placed orthogonal to the illuminating sheet plane to record the visualised droplets. The camera was fitted with a long distance microscope lens. The imager cells were rectangular and the primary magnification factor along the measurement direction, of up to 478 pixel/mm (i.e. imager pixel number on camera/actual object size) was realised with a 15× eye piece fitted into the microscope lens system. The numerical aperture for this optical configuration was 0.1. Lower magnification factors were also employed in the 33 to 128 pixel/mm range. A TSI 3450 Vibrating Orifice Aerosol Generator was used to produce uniform droplets of known size.

The dimensions of the sheet employed for droplet stream imaging comprised 0.36 mm thick by 20 mm wide. The planar laser sheet had a maximum energy density of 119 MW/cm² (or 1.8 J/cm³). This energy density level exceeded the 0.3 MW/cm² threshold level for morphology-

dependent-resonance, MDR, for drops as suggested by Bazile and Stepowski (1994). In fact MDR was found to prevail in our preliminary droplet images. To eliminate the effect of this non-linear interference on planar imaging, ionic dye molecules were dissolved in deionised water to induce fluorescence emission at a wavelength that was shifted from that of the incident beam. Water was doped with Rhodamine 6G at a concentration of 1×10^{-4} mole/litre. Long pass (OG 550) and narrow band pass filters (569±5 nm) were used to allow the wavelength shifted signals to pass through while blocking the 532 nm elastic scattering signal. Differences in the images captured by these two filter arrangements will be discussed later.

When imaging the practical spray based on the Mie scattering signal, aviation kerosine was injected from a commercial gas turbine airblast atomizer at throughputs up to 40 g/s into a quiescent environment in a pressure vessel. The air pressure drop across the injector was typically around 5% of the inlet pressure. Adequate optical access was gained through the window ports on the vessel (Figure 1). The laser beam was transformed into a sheet of 55 mm width and 0.36 mm thickness to illuminate a horizontal cross section through the centre of the spray flow-field. Different sheet thicknesses were tried to explore their influence on image quality and this will be discussed more fully in section 3. From these global images, qualitative information can be extracted to illustrate various aspects of fuel atomization and the resulting spray structure. A photographic camera was chosen because of its high resolution capability, due partly to the fine grain film. A Hasselblad camera, featuring 60 mm×60 mm black and white negative film of ISO 400 speed, was used for recording the scattering signals. A primary magnification factor of 0.5 at a working distance of about 500 mm between the illumination plane and the camera lens was selected to cover the necessary field of view for global imaging. Extension of this experiment to quantitative LIF imaging on a water spray was also performed

whereby water was doped with Rhodamine 6 G and the signals were recorded on a 15 bit CCD camera. A surfactant was added to water, to lower its surface tension to a level close to that of kerosine to ensure the relevance of the acquired results to the gas turbine application. Integrated extinction of the planar laser sheet was determined by relating the transmitted laser intensity, I , to the incident intensity, I_0 , i.e. $(1-I/I_0)$, as a measure of the average, line of sight extinction over the intercepted pathlength through the spray flow-field.

3. Results and Discussion

a) Monodisperse drop stream

For droplet imaging, five particle diameters, ranging from 47.5 to 285.3 μm , were selected as being representative of those found in practical gas turbine sprays. The choice at the lower end was mainly restricted by the increasing difficulty associated with stable aerosol generator operation. The laser sheet is considered to be thick enough to contain the whole of the drop. The images of individual drops captured by long pass filter are compared with those obtained by narrow band pass filter in Figure 2a. The high magnification achieved by the telescope lens combined with the high sensitivity of the CCD camera facilitates detailed individual drop imaging. The long pass filter cuts out Mie scattering at 532 nm only, all inelastic signals pass through which consist of LIF, stimulated Raman scattering (SRS) and lasing (Serpengüzel et al. (1992)). The high intensity at the droplet boundary is caused by total internal reflection of the light rays repeatedly around the droplet rim. The drop interior emits a mixture of LIF and SRS signals. The LIF based droplet images obtained by narrow band pass filter, on the contrary, are quite uniform over the entire cross-section. The 10 nm bandwidth filter was effective in suppressing both the green elastic scattering and the wavelength shifted red lasing and SRS signals that appear in long pass filtered images. Intensity profiles for the long and narrow band pass filtered images corresponding to the 101.5 μm particles are shown in Figures 2b and 2c. These profiles are profoundly different in character, uniform, spike

free intensity distribution for the fluorescence case in contrast to the sharp spikes due to lasing at the droplet edges followed by uniform distribution in the droplet interior for the other inelastic case.

The intensity profiles are thresholded and signals above the threshold are assumed to be from drops.

The droplet diameter can thus be calculated by counting the pixels and taking account of the relevant magnification factor.

Low magnification, and low resolution, tend to increase the sizing uncertainty as each pixel represents a large field of view and the error associated with one pixel inaccuracy will be higher compared with that for the high magnification case. Figure 3a demonstrates the effect of number of imager pixels per millimetre on the accuracy of the diameter measurement for the 101.5 μm droplets. At 478 pixel/mm, the drop diameter deduced from the LIF image is close to the actual size. This magnification was thus selected for the entire droplet imaging test. The diameters measured from narrow band and long pass filtered images in Figure 3b show good agreement, especially the LIF based ones. The larger size from long pass filtered images is due to the intensity spreading at the boundary.

Droplet sizing method adopted by Bazile and Stepowski (1994) relies on the absolute intensity level of the LIF signals, as the integrated fluorescence signal is proportional to the mass of the dye dissolved in a given drop which in turn is proportional to the volume (or diameter) of the droplet. Only an arbitrary linear relationship between the measured LIF intensity and drop size has been established by this technique. Calibration is therefore necessary for absolute size determination. Golombok and Pye (1990) looked at the spectroscopic details of the SRS signals and the diameter was evaluated by analysing the spectral spacing associated with a droplet of a given size. The sizing approach adopted here is straight forward where the drop diameter is determined directly from the intensity profile. However it requires a large number of imager elements to achieve a high degree of

accuracy. Image processing, typically intensity thresholding, will also affect the accuracy. The method is nevertheless promising for sizing of individual particles and ligaments which are currently inaccessible to commercial instrumentation. Further work is required to explore its potential for droplet imaging in practical spray flow-fields.

b) Spray global imaging

Global images depicting the structure of the spray formed by a practical twin-fluid atomizer at atmospheric pressure-temperature conditions, featuring two light sheet thicknesses, are presented in Figure 4. Thinner laser sheets will inherently yield a smaller probe volume in a given spray, and consequently illuminate fewer particles. This implies that in dense sprays, where a large number of particles may co-exist in the illuminated volume, a thinner sheet can provide more details of the flow-field by minimising the problem of co-incident particle images - cf. Figure 4. For a given width, a thinner sheet will also yield a higher energy density, which in turn can improve the signal-to-noise ratio. A light sheet of 0.36 mm thickness was obtained after due consideration of key practical issues such as the physical dimensions of the pressure vessel and the range of drop sizes expected within the spray.

Figure 5 shows some of the global, instantaneous spray views obtained by laser sheet imaging under varying kerosene fuel flow rates at ambient pressure-temperature conditions. These Mie scattering based images were obtained under constant airstream momentum conditions and provide an informative insight into the manner in which the physical structure of the spray changes as the fuel momentum varies. The radial distribution of fuel within the spray volume can clearly be seen to vary with changes in fuel flow. At high liquid flow rates, most of the fuel seems to be in the radially outer regions, resulting in a comparatively large region of low droplet concentration in the centre. These images, therefore, give a qualitative indication of the effect of fuel flow variation on spray

uniformity. Furthermore, the width of the spray plume can be observed to change with an increase in fuel flow rate.

The foregoing images can be used to determine readily the outline profile of a spray under given operating conditions. Superimposition of the profiles derived from a number of instantaneous images, as depicted in Figure 6a, can serve to illustrate the effect of injector induced, aerodynamic fluctuations upon the spray boundary. An average spray profile can thus be obtained and analysed for features such as the spray cone angle and initial diameter. Most practical sprays tend to have curved boundaries and this is confirmed by profiles shown in Figure 6a. This implies that the cone angle will vary as the spray evolves and certain axial positions, therefore, need to be specified for cone angle measurement (Parsons and Jasuja (1986)). Spray diameters were measured from the mean profiles at the nozzle exit plane as well as at 10, 27 and 45 mm along the spray axis in the downstream direction. The cone angle at a given axial position was obtained by simply drawing straight lines from the mean spray diameter at the atomizer exit to the mean spray diameter at the relevant axial location. Figure 6b reveals that under constant air momentum conditions, an increase in fuel flow and hence fuel momentum yields a reduction in the spray diameter at the injector exit plane. This is consistent with the internal liquid flow arrangement featured in the atomizer studied where the fuel is discharged tangentially towards the nozzle axis. By implication the fuel flow inside the atomizer initially adopts a convergent trajectory followed eventually by a divergent path. The location of the convergent to divergent transition point, i.e. the spray 'neck', seems to have been located inside the atomizer for the range of flow conditions covered as its presence has not been detected in all the acquired external images.

The effect of fuel flow variation on the cone angle at certain axial positions is shown in Figure 6c.

The measured cone angle reveals maximum sensitivity to fuel flow changes for the 10 mm axial

location. This position is of more practical interest to the combustor design engineer due to the need to ensure that the combustion process is effectively initiated and sustained. The increase in angular fuel momentum under fixed air velocity and hence momentum conditions contributes to the greater fuel spreading. The foregoing spray parameters could be applied as part of the input boundary conditions for computational modelling of the spray flow-field.

In gas turbine operation, an increase in fuel flow usually accompanies an increase in air mass flow and air pressure. The data from the present tests where the air flow is arbitrarily controlled serve to distinguish the effects of atomizing airstream momentum from that of the inlet fuel stream. Analysis of the atmospheric results suggests that the spray diameter at the nozzle exit plane and the initial cone angle are essentially controlled by the liquid flow. The atomizing air does not appear to exert much influence on the very near-field spray structure. This analysis will be extended in the near future to cover higher air densities in order to gain a more comprehensive understanding of the factors affecting spray placement in practical applications.

Figure 7 shows the time-averaged line of sight laser extinction encountered by the light sheet as it passes through the spray. It indicates that about half of the laser energy has been attenuated by the atomized liquid fuel at 5 g/s while for the 40 g/s fuel flow case, the laser beam has lost most of its energy. This does not seriously undermine the qualitative laser sheet imaging, as Figure 5c still shows a complete spray cross-section. In the quantitative laser induced fluorescence measurement, the incident laser beam energy directly affects the intensity of the fluorescence signal and the declining laser energy along the path through the spray will underestimate the local fuel concentration. The LIF image of Rhodamine 6G doped water spray at a flow rate of 40 g/s has an obvious asymmetry in the intensity profile when compared with that at a flow rate of 10 g/s. Here 50 instantaneous images have been averaged in both cases (Figure 8). The local fluorescence

intensity is proportional to the local liquid volume. The LIF images, therefore, provide an indication of the local fuel concentrations. However, the laser energy attenuation encountered due to the absorption by dye and scattering from particles needs to be compensated for reliable measurements in dense sprays.

4. Conclusions

Mie scattering based planar imaging has been successfully applied for global characterization of sprays. It facilitates useful insight into spray atomization including the identification of spray cone angle, structures and uniformity. Laser induced fluorescence imaging has been found to be fundamentally reliable for individual droplet measurements but the technique needs to be extended to particle size measurements in practical sprays. Excessive laser attenuation, due to high liquid concentration in dense sprays, has not been found to severely restrict Mie scattering based qualitative imaging. Reliable quantitative determination of local fuel concentration when using LIF imaging requires further work in order to effectively correct for the observed underestimation due to laser extinction problems encountered in dense sprays.

5. Acknowledgements

The authors wish to thank the EPSRC and Rolls Royce plc for a research grant (GR/H82372) which supported this study. Professor D.A. Greenhalgh is thanked for the loan of the CCD camera and the associated support. Parker Hannifin is also acknowledged for supplying the fuel injector used in the study.

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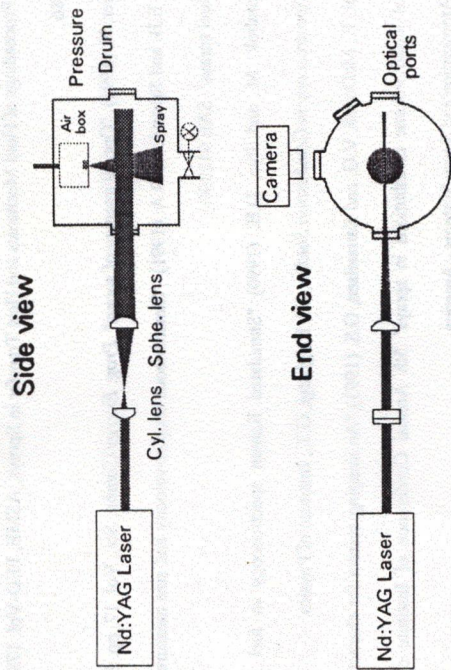


Figure 1 Schematic set up of laser imaging in the pressure vessel

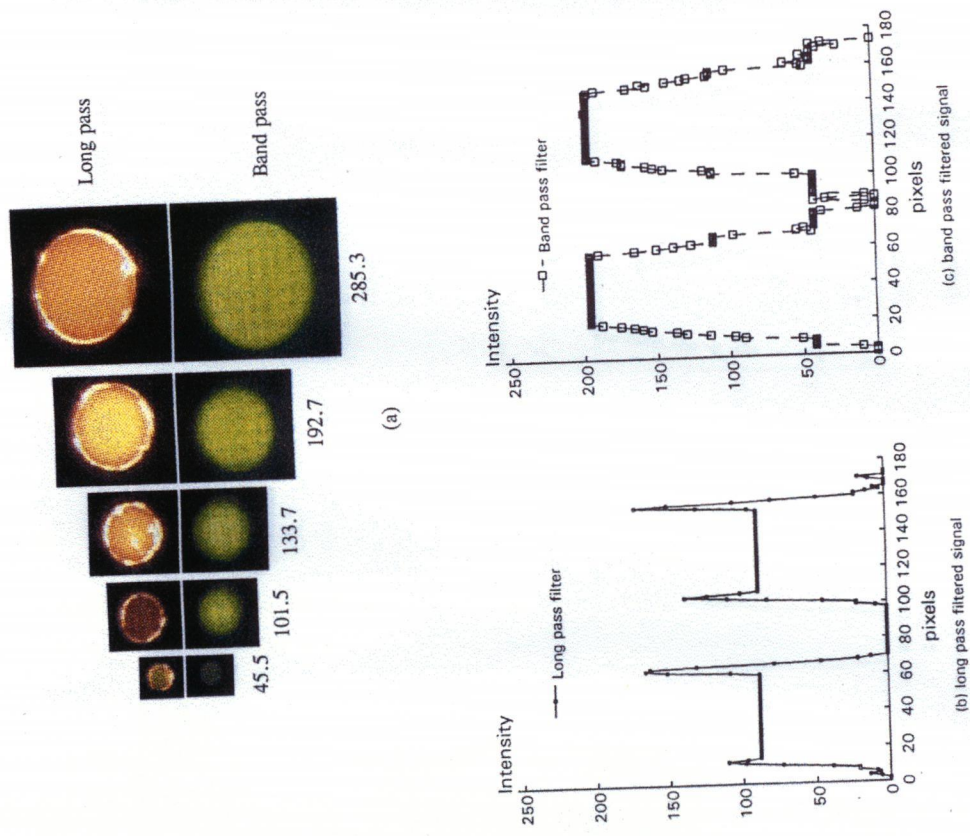


Figure 2 Monodisperse droplet imaging. Rhodamine 6 G doped water drops. (a) images when using long pass and band pass filters; (b) intensity profile for 101.5 μm drops when using long pass filter; (c) intensity profile for 101.5 μm drops when using narrow band pass filter

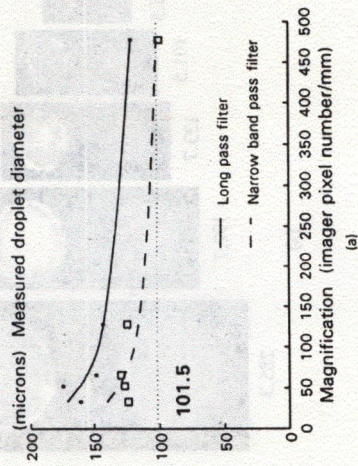
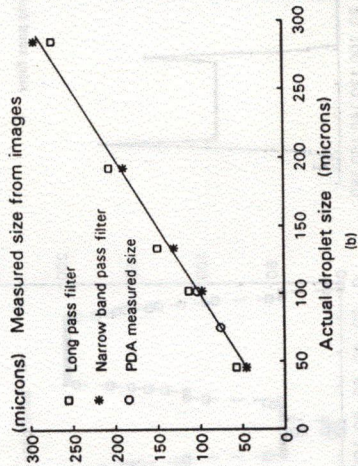


Figure 3 Droplet sizing by laser imaging. (a) Effect of magnification on the measurement accuracy; (b) Comparison of measured size with actual size

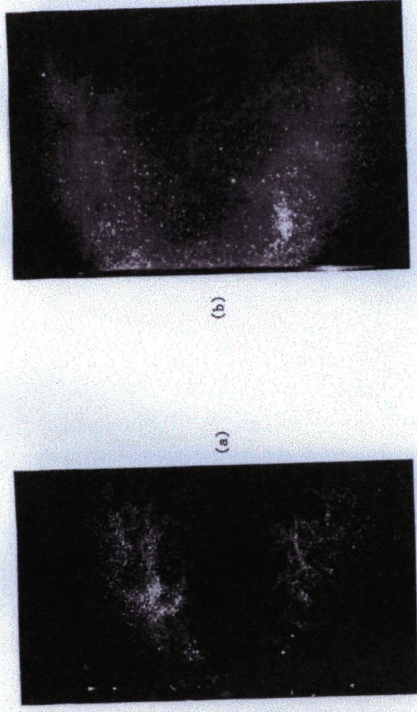


Figure 4 Spray images illuminated by laser sheets of different thickness: (a) 1.5 mm and (b) 6.5 mm

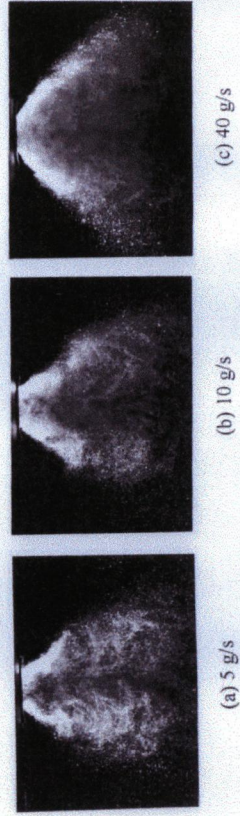


Figure 5 Laser sheet imaging of atmospheric sprays at fuel flow rate: (a) 5 g/s, (b) 10 g/s and (c) 40 g/s. The laser sheet is from left to right

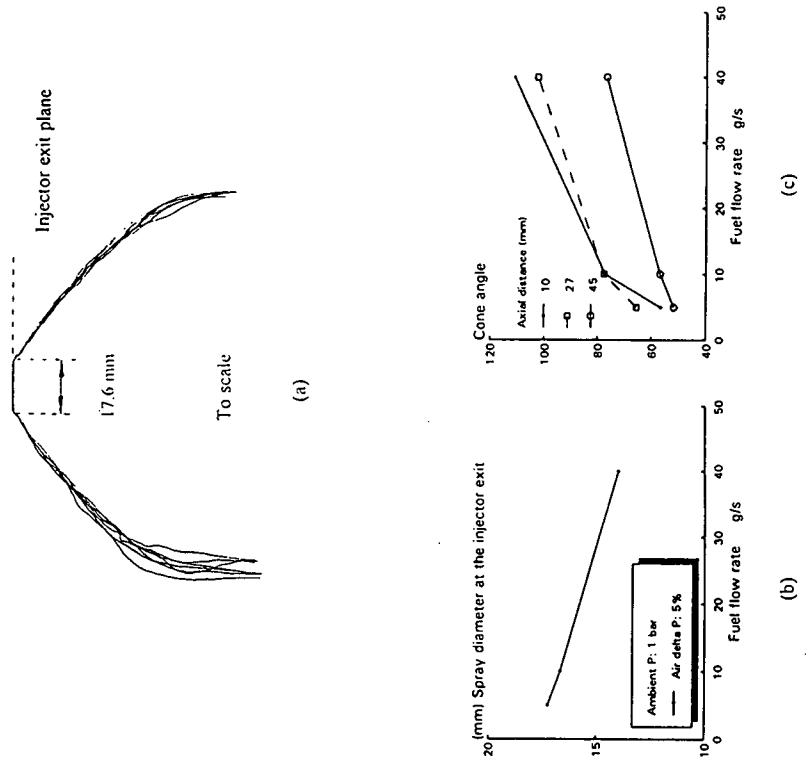


Figure 6 (a) Spray profile at the fuel flow rate of 40 g/s, 8 images are superimposed; (b) Effect of fuel flow rate on spray diameter at injector exit; (c) Effect of fuel flow rate on spray cone angle

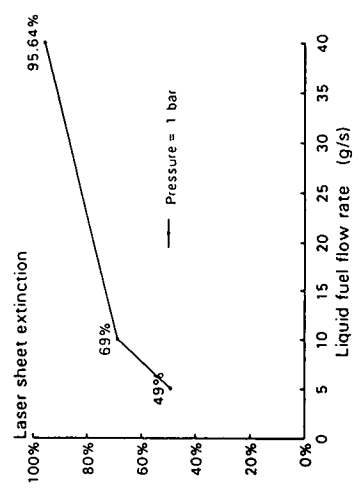
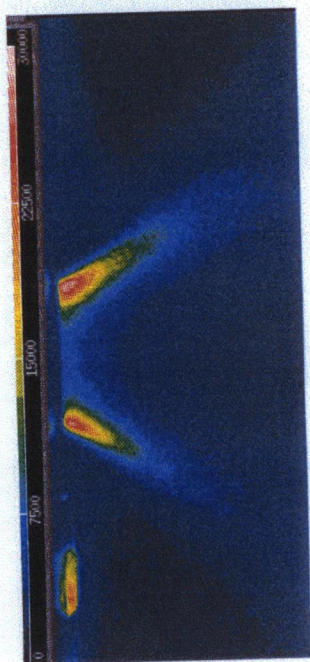
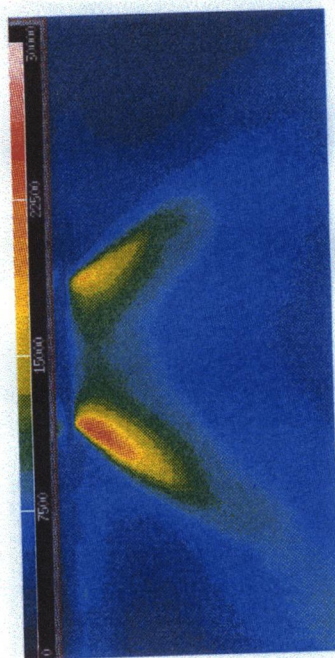


Figure 7 Effect of fuel flow rate on integrated line of sight laser sheet extinction. sheet width=20 mm



(a)



(b)

Figure 8 Laser induced fluorescence images of airblast atomizer spray. Fuel flow rate: (a) 10 g/s and (b) 40 g/s

INFLUENCE OF AIR AND FUEL FLOWS ON GAS TURBINE SPRAYS AT HIGH PRESSURES

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A single-component phase-Doppler particle analyzer (PDPA) is used to measure local variations in drop-size distributions and drop velocities in the near-nozzle region of a practical, contraswirling, prefilming airblast atomizer. The technique of laser sheet imaging is used to obtain global patterns of the spray. Measurements are taken using air pressure drops across the atomizer of 5% and 10% and ambient air pressures of 1, 6, and 12 bar. The liquid employed is aviation kerosine at flow rates of up to 75 g/s. The results show that the previously observed effect of an increase in ambient air pressure in widening the spray cone angle is not a pressure effect per se but is due to the increase in fuel flow rate that accompanies an increase in air pressure at constant air-fuel ratio (AFR). For any given air pressure, it is found that spray cone angle increases gradually and continuously with increase in fuel flow rate. If the fuel flow rate is allowed to remain constant, the effect of an increase in air pressure is to reduce slightly the spray cone angle. In general, spray volume increases with fuel flow rate and/or reductions in air pressure. Variations in air pressure at a constant AFR, which corresponds to the normal practical situation, have little effect on either spray volume or the distribution of drop sizes in the spray.

Introduction

Much of our present knowledge of airblast fuel injectors was gained during the 1960s and 1970s on atomizers in which the atomizing air was essentially coflowing and nonswirling. In recent years, the considerable advances made in the development of laser diagnostic techniques for spray characterization have generated a number of experimental studies on the basic phenomena occurring within complex practical systems of the types currently in service on advanced turbojet engines. An important design feature of all these atomizers is that the bulk fuel is first spread into a thin, continuous sheet, a process called "prefilming," and then exposed to high-velocity, swirling air streams on both sides of the sheet. Wang et al. [1,2], McDonnell et al. [3], and Hebrard et al. [4] used two-component phase-Doppler interferometry systems to make detailed measurements of drop sizes and velocities in the flows downstream of engine airblast atomizers. Jasuja and co-authors [5,6] used various nonintrusive techniques, including phase-Doppler interferometry, high-intensity spark photography, high-speed cinephotography, and video imaging to capture the dynamic and unsteady spray characteristics produced in prefilming airblast atomization. More recently, Zheng et al. [7] focused on the effects of variations in ambient air pressure

on the drop sizes and velocities produced downstream of a practical, contraswirling, prefilming airblast atomizer. The objective of the present work is to extend these previous studies to include the effects of pressure on drop-size distributions, spray cone angle, and spray dimensions. The influence of atomizer pressure drop on spray properties is also examined because the use of higher liner pressure drops represents a practical means of reducing smoke and nitric oxide emissions.

Experimental

The test facility for this study has been fully described elsewhere [5,7]. High pressure air at near-ambient temperature is used to pressurize a large cylindrical vessel and is delivered to the fuel injector that is located at one end of the vessel and is arranged to spray horizontally along its major axis.

Atomizer

A cross-sectional view of the fuel injector employed is shown in Fig. 1. It is a prefilming airblast atomizer that is typical of those used in modern gas turbine engines. It features a pair of concentric air inlets that generate two separate swirling air flows in opposite directions. The design objective is to create a thin, annular sheet of fuel that is then sandwiched between the two swirling air streams. This

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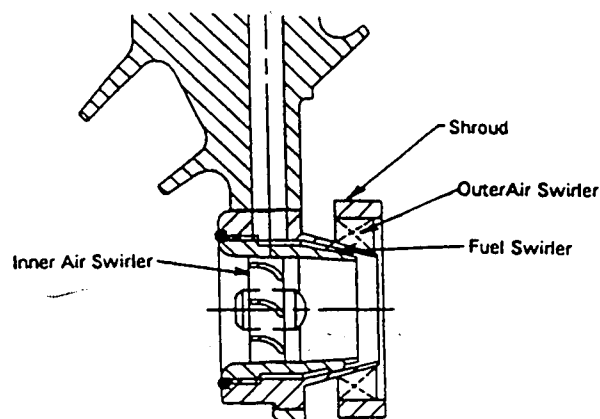


FIG. 1. Schematic diagram of airblast atomizer (courtesy of the Parker Hannifin Corporation, Gas Turbine Fuel Systems Division).

configuration generates a high shearing action between the fuel and the atomizing air that promotes atomization and helps to match the resulting spray with the combustor air flow pattern.

Optical Diagnostics

Optical access into the pressure vessel is provided by four optical-quality quartz windows. Each of these large windows has a multipoint purge feed of high-velocity air to prevent fuel deposition. Droplet sizes and velocities were measured using a single-component phase-Doppler particle analyzer (PDPA) manufactured by Aerometrics, Inc. The instrument was operated in the forward-scattering mode, with its velocity component arranged to coincide with the main axis of the conical spray. PDPA data were normally taken at a downstream distance from the atomizer exit plane of 45 mm along radii perpendicular to the spray axis. The technique of laser sheet imaging was used to obtain global images of the spray. With this technique, a pulsed Nd:YAG laser beam is converted into the form of a 0.4-mm-thick sheet that illuminates the spray flow field under investigation. The system provides a power density of 27 MW/cm² in the laser sheet probing volume. The elastic-scattering signals at a wavelength of 532 nm were recorded on black and white film, of ISO 400 speed, positioned perpendicular to the laser sheet. The laser pulse duration of 15 ns is generally considered short enough to freeze the particle motion. A primary magnification factor of 0.5 was selected to provide a field of view that is typical of current combustor primary-zone lengths.

Test Conditions

The test conditions were selected to correspond to those encountered in gas-turbine combustors. Most of the measurements were taken with a pres-

sure drop across the atomizer, $\Delta P/P_A$ of 0.05, i.e., 5%, but a small number of measurements were also carried out at a higher $\Delta P/P_A$ of 0.10 in order to examine the effects of atomizing air velocity on spray structure and mean drop size. Atomizer air-fuel ratios (AFRs) ranged from 1.1 to 58. The ambient air pressures employed were 1, 6, and 12 bar at an air temperature of about 320 K. At the 12 bar condition, the maximum air and fuel mass flow rates were 0.29 kg/s and 75 g/s, respectively. Aviation kerosine ($\mu = 0.0013$ kg/ms, $\sigma = 0.0277$ kg/s², and $\rho = 784$ kg/m³—all at 288 K) was used throughout the test program.

Results

One phase of the test program was devoted to photographic studies using pulsed laser sheet lighting to illuminate the spray. The main objective was to examine the extent to which the overall size and shape of the spray is affected by changes in air pressure, air velocity, and fuel flow rate. Such information helps to provide a better understanding of the effects of these parameters on various aspects of combustion performance.

Spray Structure

Figure 2 shows how the physical structure of the spray is affected by an increase in ambient air pressure P_A from 1 to 12 bar while maintaining the fuel flow rate m_F constant at 35 g/s. The corresponding measurements of spray diameter at different axial locations, z , downstream of the nozzle are shown plotted in Fig. 3. All values of spray diameter shown in this and subsequent figures were obtained from high-speed photographs as an average of eight individual, instantaneous diameters measured up to the outermost visible boundaries of the spray profile. Figures 2 and 3 indicate a rapid expansion of the spray as it emerges from the nozzle which is caused by the swirling motion that is imparted to the two atomizing air streams as they flow through the contrarotating swirl vanes. From visual inspection of Fig. 2, it is clear that the effect of an increase in ambient air pressure is to reduce the spray volume. This effect is shown quantitatively in Fig. 3, which indicates a reduction in spray diameter from 80 mm to about 50 mm for an increase in air pressure from 1 to 12 bar. These measurements were carried out at a downstream distance from the atomizer of 27 mm. (Measurements taken further downstream tend to be less reliable due to fluctuations of the spray boundaries, as determined from high-speed photographs, which are attributed partly to the eddies generated by the shearing action of the two contrarotating swirling air flows and also to the formation of coherent structures at the interface between the

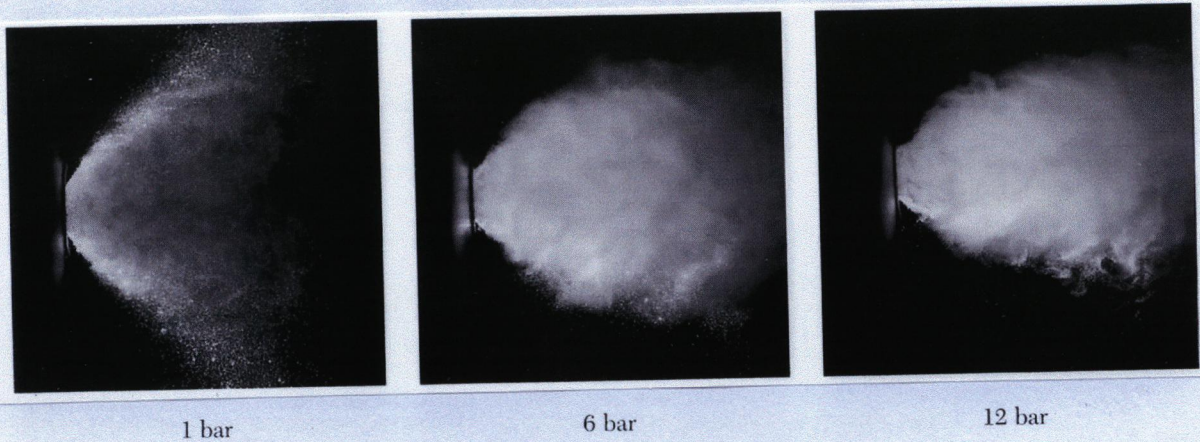


FIG. 2. Influence of air pressure on spray structure for a constant fuel flow rate of 35 g/s and $\Delta P/P_A$ of 0.05.

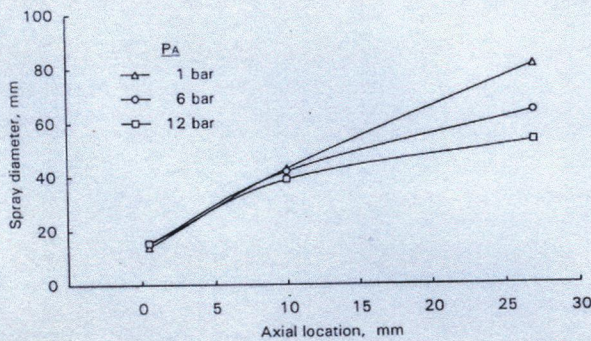


FIG. 3. Influence of air pressure on spray diameter for a constant fuel flow rate of 35 g/s and $\Delta P/P_A$ of 0.05.

high-velocity spray boundary and the surrounding quiescent air. Moreover, the trailing edges of the spray in Fig. 2 reveal less structural details than the leading edges due to attenuation encountered by the laser light sheet along its pathway through the dense spray flow field. This gives an apparent impression of spray asymmetry when in fact none is known to be present.

The observed reduction in spray diameter with increase in air pressure is not due to any change in air flow pattern, because Reynolds numbers are always high ($\gg 10^6$), but rather to the reduction in the fuel-air momentum ratio, which accompanies an increase in air pressure at constant fuel flow. As in most practical prefilming airblast atomizers, the "natural" cone angle of the spray, i.e., the angle of the spray in the absence of any atomizing air, is much wider than the angle imparted to the air by the air swirlers incorporated within the atomizer. When the atomizing air first encounters the conical fuel sheet formed at the downstream edge of the prefilmer, it tends to reduce the ensuing spray diameter by an amount that depends on the ratio of air to fuel momentum, as illustrated in Figs. 2 and 3.

In the course of the test program, a considerable

body of evidence was accumulated, all of which tended to confirm the overriding importance of the fuel-air momentum ratio to spray diameter and spray volume. For example, Figs. 4 and 5 show the effects on spray dimensions of an increase in fuel flow rate from 5 to 75 g/s (corresponding to a reduction in AFR from 58 to 3.9) while maintaining the air pressure constant at 12 bar. These figures show clearly that increases in fuel-air momentum ratio, produced in this case by increases in fuel flow rate at constant air pressure, result in larger spray diameters. This influence of fuel-air momentum ratio on spray dimensions has important practical implications, one obvious example being the risk of fuel impingement on the liner walls at high fuel flow rates. In general, this influence of fuel-air momentum ratio on spray structure is beneficial to combustion performance. For example, a reduction in fuel flow rate at constant pressure causes the fuel to be associated with a smaller volume of air, thereby extending the lean blowout limit to a higher value of AFR. By the same token, an increase in fuel flow rate at constant pressure is accompanied by an increase in the amount of air participating in combustion. The effect of this additional air is generally to reduce the local fuel-air ratio and flame temperature, thereby alleviating problems of exhaust smoke and nitric oxide emissions at high combustion pressures.

Measurements carried out on the effects of atomizer pressure drop on spray size and structure yielded results that are generally consistent with the views expressed above. Thus, an increase in $\Delta P/P_A$ from 0.05 to 0.10, corresponding to a doubling of atomizing air-fuel momentum ratio, would be expected to reduce the spray diameter, and this is confirmed by the data presented in Fig. 6.

Gas turbines normally operate under conditions when an increase in combustion pressure is accompanied by an increase in fuel flow rate. Thus, the

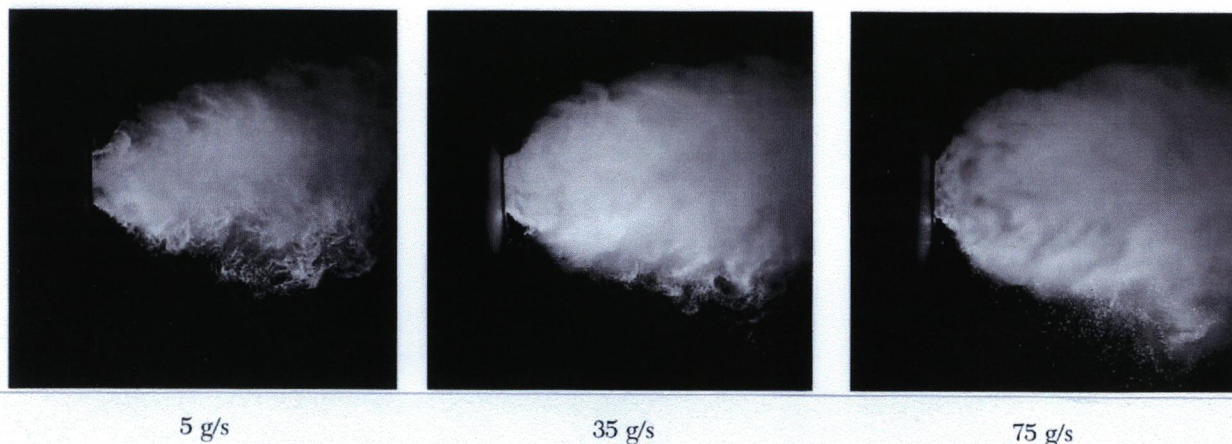


FIG. 4. Influence of fuel flow rate on spray structure for a constant air pressure of 12 bar and $\Delta P/P_A$ of 0.05.

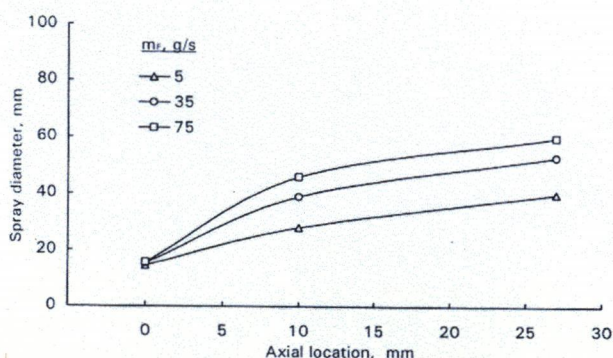


FIG. 5. Influence of fuel flow rate on spray diameter for a constant air pressure of 12 bar and $\Delta P/P_A$ of 0.05.

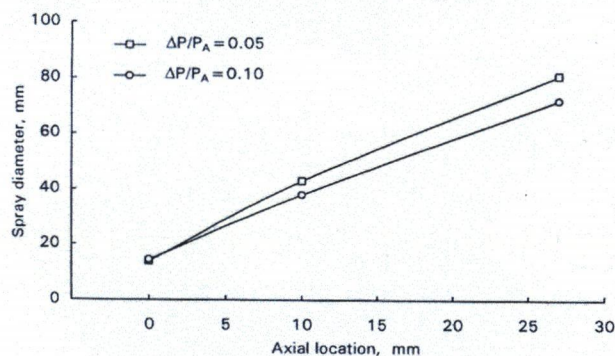


FIG. 6. Influence of $\Delta P/P_A$ on spray diameter for a constant air pressure of 1 bar and fuel flow rate of 35 g/s.

effect of an increase in pressure in reducing spray volume is opposed by the attendant increase in fuel flow rate that tends to increase the spray volume. The net result is that changes in air pressure at constant AFR have relatively little effect on spray diameter, except in the near-nozzle region ($z \approx 10$ mm).

Figures 2 and 4 show that as the droplets move downstream, the spray boundaries, which initially

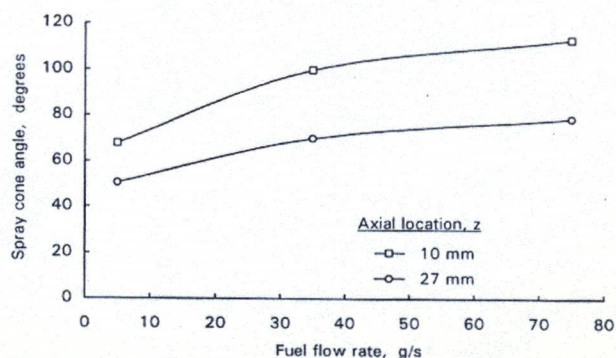


FIG. 7. Influence of fuel flow rate on spray cone angle for a constant air pressure of 12 bar and $\Delta P/P_A$ of 0.05.

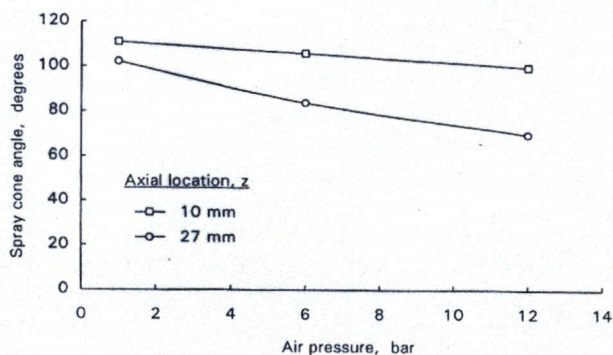


FIG. 8. Influence of air pressure on spray cone angle for a constant fuel flow rate of 35 g/s and $\Delta P/P_A$ of 0.05.

are in the form of a straight cone, start to become curved due to momentum exchange with the surrounding air. These curved boundaries create difficulties in the definition and measurement of cone angle. A further complication is caused by the fact that the initial diameter of the spray as it emerges from the nozzle is not only different from that of the prefilming edge but can also vary with changes in atomizer operating conditions.

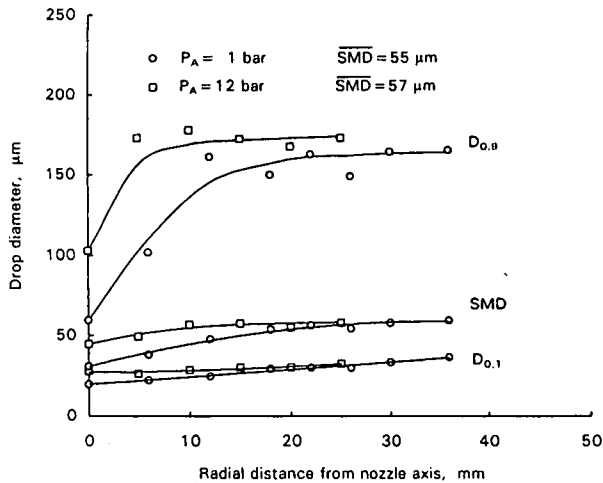


FIG. 9. Influence of air pressure on drop size distributions for a constant AFR of 3.9, $\Delta P/P_A$ of 0.05, and $z = 45$ mm.

The cone angles obtained by drawing straight lines from the spray diameter at the nozzle exit to the mean spray diameter (obtained as the average of several measured spray profiles), at certain specified distances downstream of the nozzle, are presented in Figs. 7 and 8. Figure 7 illustrates the influence of fuel flow rate on spray cone angle for an ambient air pressure of 12 bar. The influence of air pressure on cone angle is shown more directly in Fig. 8 over a range of air pressures from 1 to 12 bar. All the results contained in these figures are fully consistent with the notions expressed above in regard to the overriding importance of fuel-air momentum ratio to the size and shape of the spray. Essentially, the swirling and recirculating air flow patterns created by the air swirlers are independent of combustor operating conditions, and thus, the overall dimensions of the aerodynamic recirculation zone also tend to remain fairly constant. However, the spray boundaries and the radial distribution of fuel flux within the spray boundaries are both modified appreciably by changes in combustor operating conditions, mainly in so far as these changes influence the fuel-air momentum ratio of the nozzle efflux. Thus, the widening of spray cone angle with increase in fuel flow rate, as shown in Fig. 7, can be attributed directly to the concomitant increase in fuel-air momentum ratio. If a change in atomizer operating conditions should cause this ratio to decline, then the spray cone angle must also decline, as illustrated in Fig. 8. This figure shows the effect on cone angle of increasing the air pressure while maintaining the fuel flow rate constant. As expected, the reduction in fuel-air momentum ratio associated with an increase in pressure at constant fuel flow causes the cone angle to go down. However, for the more practical case in which an increase in pressure at constant AFR produces an increase in fuel-air momentum ratio,

the spray cone angle actually increases in the near-nozzle region [7].

These same arguments would suggest that an increase in nozzle pressure drop at constant fuel flow rate should reduce the spray cone angle. This was confirmed by spray photographs, which showed the effect of doubling the nozzle pressure drop from 5% to 10% of the inlet pressure while keeping the fuel flow rate constant. The effect of increasing $\Delta P/P_A$ was to reduce the spray cone angle, in this case, by about 10° .

Drop Size Distributions

In two recent experimental studies on the droplet velocities and drop-size distributions obtained from practical prefilming airblast atomizers [5,7], it was shown that an increase in ambient air pressure at constant AFR could result in either a small increase or a small decrease in integrated Sauter mean diameter ($\overline{SMD}$), depending on the initial rate of interaction between the fuel and the atomizing air. In these previous studies, attention was focused mainly on the factors influencing local values of SMD within the spray volume and on $\overline{SMD}$. In this test program, an attempt was made to shed some light on the apparent insensitivity of $\overline{SMD}$ values to variations in air pressure by examining two representative diameters in addition to SMD.

The effects of increasing the air pressure from 1 to 12 bar on the radial distribution of $D_{0.1}$ (the drop diameter such that 10% of the fuel is in drops of diameter smaller than $D_{0.1}$), SMD, and $D_{0.9}$ (the drop diameter such that 90% of the fuel is in drops of diameter smaller than $D_{0.9}$) are demonstrated in Fig. 9 in which local measured values of $D_{0.1}$, SMD, and $D_{0.9}$ are shown plotted against radial distance from the centerline of the spray. For all measurements, the fuel flow rate was adjusted to maintain a constant AFR of 3.9. Figure 9 shows very little difference in local values of $D_{0.1}$, SMD, and $D_{0.9}$ at the two different levels of pressure. Although the local values of $D_{0.9}$ for small radial distances are clearly lower at the 1 bar pressure, this has little effect on $\overline{SMD}$ because most of the fuel is contained in the outer regions of the spray.

The $\overline{SMD}$ values were obtained as the mean of all the local measured values of SMD after each local value had been corrected using appropriate area and velocity weighting factors to account for the higher flow areas in the outer regions of the spray and the nonuniformity of the radial velocity distribution. Application of this procedure to the local SMD data contained in Fig. 9 revealed only a small difference in $\overline{SMD}$ between measurements carried out at 1 and 12 bar, being $55 \mu\text{m}$ in one case and $57 \mu\text{m}$ in the other. In all tests, the influence of air pressure on $\overline{SMD}$ was found to be quite small in comparison to

the effect of AFR [7]. It may be concluded therefore that not only is $\overline{SMD}$ largely independent of pressure, but so also is the distribution of drop sizes within the spray. Tests on the influence of nozzle pressure drop on mean drop size showed, as expected, that an increase in $\Delta P/P_A$ resulted in a reduction in $\overline{SMD}$. For example, measurements carried out at a distance of 27 mm downstream of the atomizer at normal atmospheric pressure showed that increasing $\Delta P/P_A$ from 0.05 to 0.10 reduced the $\overline{SMD}$ from 68 to 55 μm .

Conclusions

A series of measurements of mean and representative drop diameters, spray dimensions, and spray cone angles has been carried out on a practical, pre-filming airblast atomizer of the type widely used in modern gas turbines. From tests using kerosine fuel and atomizing air at pressures up to 12 bar, the following conclusions are drawn:

1. The effect of an increase in ambient air pressure in widening the spray cone angle is not a pressure effect per se but is due to the increase in fuel flow rate that accompanies an increase in air pressure at constant AFR. For any given air pressure, the spray cone angle increases gradually and continuously with increase in fuel flow rate. If the fuel flow rate is allowed to remain constant, the effect of an increase in air pressure is to reduce slightly the spray cone angle. In general, spray volume increases with fuel flow rate and/or reductions in air pressure. Variations in air pressure at a constant air/fuel ratio, which corresponds to the normal practical situation, have little effect on spray volume. It is concluded that the main factor governing the spray cone angle and overall dimensions of the spray is the fuel-air momentum ratio. Increases in this parameter result in wider cone angles, larger spray diameters, and a displacement of the fuel flux profile toward the outer regions of the spray.
2. For the practical type of airblast atomizer employed in this investigation, variations in ambient air pressure from 1 to 12 bar have little effect on drop size distributions in the spray.
3. Increasing the air pressure drop across the atomizer reduces not only the mean drop size but also the spray cone angle.

Acknowledgments

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An Investigation into Internal/External Liquid Trajectory Behaviour of a Gas Turbine Airblast Atomizer

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Abstract

The structure of dense practical sprays produced by a commercial, prefilming airblast atomizer over a range of ambient air pressures and kerosine flow rates is explored using Mie scattering based, planar laser sheet imaging technique. Fuel/air momentum ratio is found to strongly influence the uniformity, overall dimensions and cone angle of the spray. The external fuel trajectory is linked to that prevailing within the atomizer. A hypothesis discussing the impact of fuel/air momentum ratio on this trajectory coupling is outlined. The implications of these findings to the atomizer design process are also considered.

Introduction

Originally introduced as a measure to alleviate smoke emissions from turbojet engines, prefilming airblast atomizers are now employed in a wide range of aircraft, industrial, and marine gas turbines. A key feature of all such atomizers is that the bulk fuel is first spread into a thin continuous sheet, a process called "prefilming", and then exposed to high-velocity, swirling air streams on both sides of the sheet.

In recent years considerable advances have been made in the development of laser diagnostic techniques for spray characterisation. These developments have led to a resurgence of interest in determining the properties of sprays produced in prefilming airblast atomization. Efforts are now under way to gain a better understanding of the basic phenomena occurring within complex practical systems of the types currently in service on advanced turbojet engines. Extensive, point-wise droplet size/velocity measurements have been undertaken by several research groups using phase Doppler interferometry, PDI, on a variety of practical airblast atomizers operating under widely varying conditions of liquid-air throughput, air velocity-density and liquid properties - see references 1 to 5 for example. In contrast, knowledge concerning other spray characteristics such as cone angles, droplet movement patterns, droplet concentration, status of liquid at injector exit, liquid trajectory etc., remains far from satisfactory in respect to practical atomizers. Recent research at Cranfield has explored the coupling between airblast atomizer operating conditions and the ensuing cone angle-spray uniformity in the near-nozzle region using planar laser sheet imaging, LSI, embracing both induced fluorescence and Mie scattering approaches [6,7]. The objective of this paper is to extend the previous analysis of the external fuel trajectory and to explore its possible coupling to the trajectory prevailing within the atomizer. The underlying motivation here is to have a better grasp of the design-performance trade-offs affecting mixture preparation initially, and emissions eventually.

Experimental

A cross-sectional view of the fuel injector employed is shown in Fig. 1. It is a prefilming airblast atomizer which is typical of those used in modern gas turbine engines. It features a pair of concentric air inlets which generate two separate swirling air flows in opposite directions. The design objective is to create a thin, uniform sheet of fuel on an annular prefilming surface and to then sandwich it between two swirling air streams. This configuration generates a high shearing action between the fuel and the atomizing air which promotes good atomization and also helps to match the resulting spray with the combustor air flow pattern that envelops it. The fuel injector is fitted into a high-pressure air box located inside the test vessel.

Measurement access into the test vessel is provided by four optical-quality quartz windows. Each of these large windows has a multi-point purge feed of high velocity air to prevent fuel deposition. The technique of laser sheet imaging was used to obtain global images of the spray. With this technique, a pulsed Nd:YAG laser beam is converted into the form of a 0.4 mm thick sheet which illuminates the spray flowfield under investigation. The system featured a power density of 27 MW/cm² in the laser sheet probing volume. The elastically scattered Mie signals at a wavelength of 532 nm were recorded on black and white film of ISO 400 speed positioned perpendicular to the laser sheet. The laser pulse duration of 15 nano-seconds is generally considered short enough to freeze the particle motion. A primary magnification factor of 0.5 was selected to provide a field of view that is typical of current combustor primary-zone lengths. More experimental details can be found in Ref. 5.

The test conditions were selected to simulate those encountered in gas turbine combustors. Most of the measurements were taken with a pressure drop across the atomizer, $\Delta P/P_A$, of 0.05, i.e. 5 percent, which is typical of modern combustors, but a small number of measurements were also carried out at a higher $\Delta P/P_A$ of 0.10 in order to examine the effects of atomizing air velocity on spray structure. Atomizer air/fuel ratios ranged from 1.1 to 58. The ambient air pressures employed were 1, 6 and 12 bar. At the 12 bar condition, the maximum air and fuel mass flow rates were 0.3 kg/s and 75 g/s respectively. Aviation kerosine ($\mu = 0.0013$ kg/ms, $\sigma = 0.0277$ kg/s² and $\rho = 784$ kg/m³ - all at 288K) was used throughout the tests reported.

Results and Discussion

One of the main objectives for developing advanced laser diagnostics is the need to obtain a better understanding of the spray-droplet processes prevailing within the near-nozzle region. From a combustion viewpoint, this is a zone of special importance because of its role in initiating and sustaining the combustion process. Furthermore, detailed computational modelling of the combustion process invariably requires accurate definition of the near-nozzle spray characteristics as an input boundary condition. Non-spherical particles and/or high spray densities, however, are often found in such regions - thus inhibiting reliable drop size determination. LSI technique is capable of providing useful insight concerning the overall spray size, shape, uniformity and movement pattern changes from within such a region as a result of changes in injector operating conditions.

Figure 2 shows some global, instantaneous spray views obtained using LSI at a kerosine flow rate of 75 g/s and 12 bar ambient air pressure inside the test vessel. The test condition for these multiple images corresponds to an atomizer air-to-fuel ratio, AFR, of 3.9 at a $\Delta P/P_A$ of 0.05. Images corresponding to other operating conditions can be seen in References 5-8.

These images reveal a rapid expansion of the flow-field as the spray emerges from the nozzle. The core regions of the spray that were essentially hollow at 1 bar ambient pressure have, as a result of prevailing mixing-transport processes, been filled up - i.e. at high ambient pressures droplets have undergone a radial re-distribution. As observed before, these images reveal the curved nature of the spray boundaries due to the effects of air entrainment at the interface with the surrounding flow-field. Collection of multiple images at a nominally identical operating condition is one way of gaining an insight into the dynamic nature of a given spray. A close examination of these and other high speed images suggests the formation of coherent structures at the interface between the high-velocity spray boundary and the surrounding quiescent air. In addition, the shearing action of the two contra-rotating swirling air streams results in the generation of eddies. These effects combine together to cause the spray boundaries to fluctuate as can be seen clearly in Fig. 3. This figure has been constructed through super-position of individual outline profiles derived from a number of instantaneous images, eight in this instance, for an ambient air pressure of 12 bar and an AFR of 3.9. It is clear from this figure that the amplitude of the fluctuations encountered increases as the spray evolves axially. An increase in ambient air pressure at a constant atomizer AFR of 3.9 and $\Delta P/P_A$ of 0.05 does not seem to materially affect the pulsation amplitude - the 12 bar amplitude measurements being almost identical to those at 1 bar. This is not entirely surprising since the overall aerodynamic patterns do not substantially change with an increase in ambient pressure because the Reynolds numbers are invariably high ($>> 10^6$). It should be stressed however, that with this type of injector there is no experience whatsoever of any kind of combustion instability. The situation here would seem to be akin to the eddy shedding associated with many types of bluff-body flame holders under cold-flow conditions which are found to be absent under burning conditions. Use has been made of the outermost visible boundaries of the spray from the various instantaneous profiles for superposition purposes. It should also be mentioned that leading edges of the spray reveal greater structural detail relative to the trailing edges due to attenuation encountered by the laser light sheet along its pathway through the dense spray flow-field. This could give an apparent impression of spray asymmetry where none is actually present.

The super-position technique allows an informative and reasonably accurate "mean" spray profile to be constructed for a given set of operating conditions. This average profile can then be analyzed for fuel placement parameters such as the spray cone angle - trajectory. The curved spray boundaries imply that the cone angle will vary as the spray evolves and that certain axial positions will, therefore, need to be specified for cone angle measurement - as is invariably the case with most practical sprays. Mean profiles were measured for spray diameters at the nozzle exit plane as well as at distances of 10, 27 and in some instances of up to 45 mm from the outlet along the spray axis in the downstream direction. The cone angle at a given axial position was obtained by simply drawing straight lines from the mean spray diameter at the atomizer exit to the mean spray diameter at the relevant axial location. Figures 4 and 5 show the variation in cone angle with fuel flow rate for 1 and 12 bar ambient air pressure levels, respectively. The atomizer air pressure drop is maintained at a constant level of 5 percent for both cases. These figures show that an increase in fuel to air momentum ratio, in this case achieved by increases in fuel flow while maintaining constant air density and air velocity, results in an increase in spray cone angle at all axial locations. However, the cone angle increase reveals maximum sensitivity for the 10 mm axial location - a position that is of considerable practical importance to the combustor design engineer due to the need to ensure that the combustion process is effectively initiated and sustained. Other data featuring a

reduction in fuel to air momentum ratio, achieved through an increase in either air pressure or air velocity while keeping the fuel flow rate constant, resulted in a decrease in cone angle. These findings are consistent with the observation that for most practical atomizers, including the one studied here, the fuel-alone (i.e. 'natural') cone angle is wider than that adopted by the airstream emerging from the air swirlers incorporated within the injector. Fuel/air momentum ratio is, clearly therefore, a key parameter that strongly influences the cone angle and overall dimensions of the spray.

Figure 6 shows the variation in spray diameter at the injector exit with fuel flow rate over the 1 to 12 bar ambient air pressure range. The $\Delta P/P_A$ is 5 percent for all the data points except for the single point denoted by *. This * point corresponds to 10 percent $\Delta P/P_A$ at 1 bar ambient air pressure. These results show that an increase in fuel flow from 5 to 40 g/s at 1 bar air pressure yields a significant reduction in the spray diameter at the injector exit. Fuel flow increases at 12 bar air pressure, on the other hand, have an opposite effect on this exit spray diameter, i.e. exit diameter increases throughout with fuel flow. At 6 bar air pressure, the measurements reveal a mixed trend - an increase in spray diameter initially followed by a decrease as the fuel flow continues to increase. The effect of air pressure drop on spray exit diameter can be ascertained by comparing the solitary point denoted by * obtained at $\Delta P/P_A$ of 0.10 with the data point directly below it featuring $\Delta P/P_A$ of 0.05 - the air pressure and fuel flow conditions for both of these points being 1 bar and 40 g/s. This limited comparison reveals that an increase in $\Delta P/P_A$ increases the exit spray diameter.

An explanation for these seemingly random trends can be found by invoking momentum considerations. The spray diameter at the injector exit and the near-nozzle cone angle are for all practical purposes a result of the internal fuel-air interactions. Considering first the 1 bar case - an increase in fuel flow rate yields a reduction in exit spray diameter (see Fig. 6) and an increase in near-nozzle cone angle (see 10 mm location in Fig. 4), and vice versa. This observation is linked to the internal fuel trajectory as shown on an enlarged cross-sectional view of the nozzle in Fig. 7. The design utilised employs a convergent, annular pre-filming surface i.e. the swirling fuel is discharged tangentially towards the nozzle axis. This means that the fuel inside the atomizer initially adopts a convergent trajectory followed eventually by a divergent path some time after leaving the pre-filmer. As the fuel momentum increases, it continues to follow in the initial direction imparted to it by the convergent pre-filmer for a longer distance before changing over to the divergent trajectory. This results in a reduction of the exit spray diameter (accompanied by an increase in near-nozzle cone angle as already discussed). One implication of this reasoning is that the location of the convergent to divergent transition point, i.e. the spray 'neck', moves with changes in fuel momentum. At low fuel momentum its location is at or close to the pre-filming lip while at high fuel momentum it shifts downstream as shown in Fig. 7. As the spray neck was not detected in all the acquired external images, it must have been located inside the atomizer throughout these tests. Considering next the 12 bar air pressure and 75 g/s fuel flow condition - the high fuel momentum means that the fuel would be expected to continue to follow the convergent trajectory acquired from the pre-filmer for a longer distance. As it continues to converge, it penetrates farther into the airstream delivered by the inner air swirler. At low air pressures it achieves this readily but, as the air pressure increases, it is less successful in penetrating into the high density inner swirling airstream. The accompanying decrease in fuel/air momentum ratio, due to the increase in air pressure, causes the spray neck to move upstream. Consequently, for the 75 g/s fuel flow condition, the exit spray diameter at 12 bar air pressure level is much larger than the corresponding one at 1 bar. At low fuel flow/momentum, the fuel

would be expected to follow a divergent path immediately downstream of the pre-filming lip i.e. the fuel would be expected to move more into the outer swirling air. Again at high air pressures/momentum, the fuel penetration into the outer air is inhibited due to adverse local fuel/air momentum ratio. A consequence of this is that at 5 g/s fuel flow, the exit spray diameter reduces from about 17 mm at 1 bar air pressure level to around 14.5 mm at 12 bar. This suggests that for a convergent prefilmer the exit spray diameter is influenced primarily by the outer swirling airstream at low fuel/air momentum ratios, whereas at high fuel/air momentum ratios it is the inner swirling airstream that exerts the dominant influence. The same reasoning can be applied to the other data points on Fig. 7 including the effect of atomizer air pressure drop on exit spray diameter. It is clear from this that fuel/air momentum ratio is a parameter of great importance in respect of both internal and external liquid trajectories.

The above hypothesis has interesting implications for the atomizer design-performance correlation. The traditional simplistic approach seems to have been to merge the various atomizing airstreams into one when reviewing the ensuing spray behaviour/performance. No attempt appears to have been made to explore and identify their individual regimes of influence. Similarly the momentum splits between the various contributing airstreams could, when optimized, afford improvements in near-nozzle two-phase spray behaviour. The above findings clearly relate to the design geometry studied i.e. a converging pre-filmer along with contrarotating twin airstreams. Variations in pre-filmer design, number of airstreams and their rotational direction, fuel and air swirl angle/strength and other atomizer design features could all greatly influence the nature and extent of fuel-air internal/external interactions with important implications for mixture preparation/placement and pollutant emissions.

Conclusions

Usefulness of a Mie scattering based LSI technique in acquiring basic insight into parameters of mixture placement such as fuel trajectory, spray dynamics and uniformity has been demonstrated for a range of dense practical sprays. The broad conclusions drawn from the reported work featuring converging prefilmer and contrarotating twin airstreams are:

- 1) Fuel/air momentum ratio strongly influences the cone angle and the overall size of the spray. Increases of this ratio give larger cone angle and larger spray dimensions.
- 2) Fuel/air momentum ratio largely controls the spray diameter at the exit of the injector. The internal fuel trajectory appears to be more influenced by the outer swirling air at low momentum ratios while the inner swirling airstream exercises the dominant influence at high momentum ratios.

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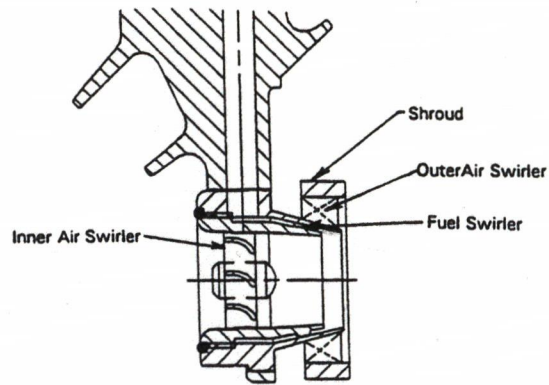


**Fig. 1 Schematic diagram of airblast atomizer
(Courtesy of Parker Hannifin Corp.)**

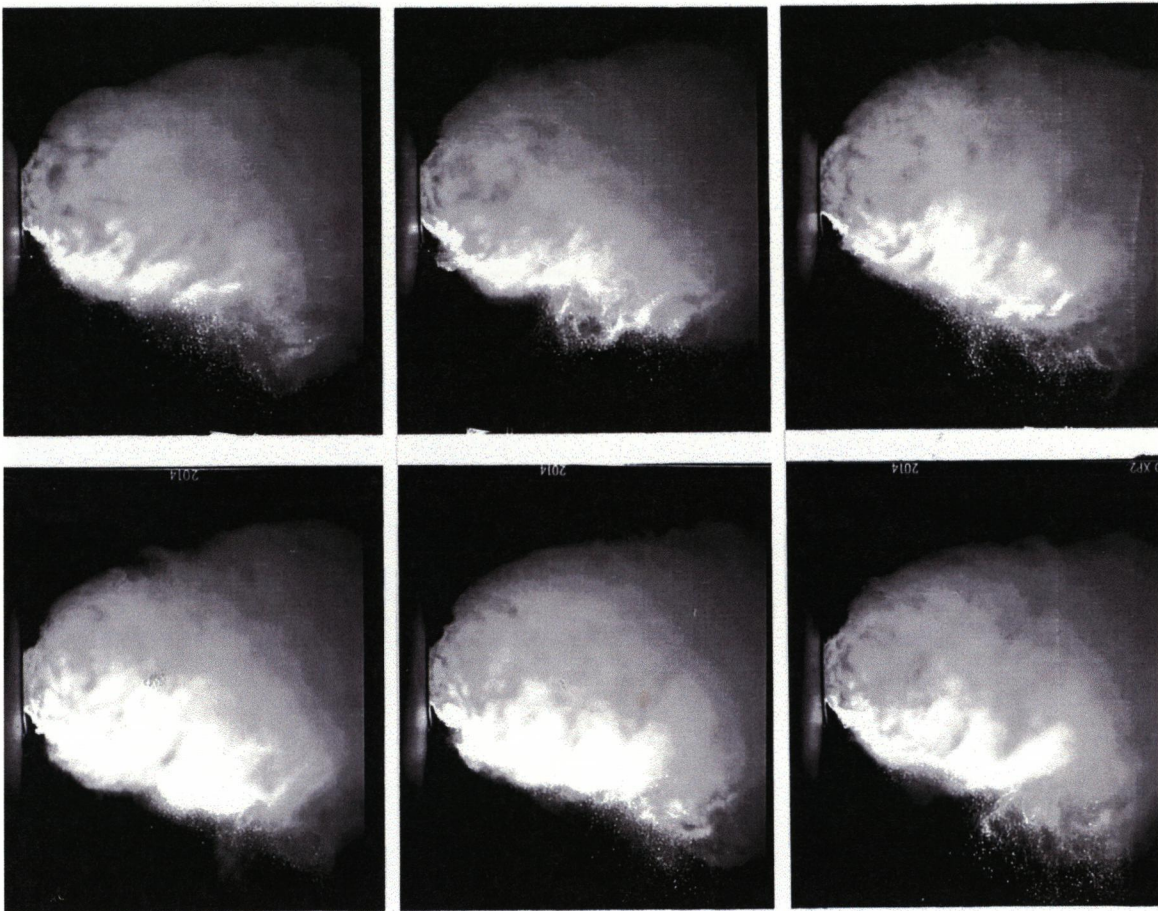


**Fig. 2 Multiple, instantaneous spray images
- 12 bar air pressure, 75 g/s fuel flow**

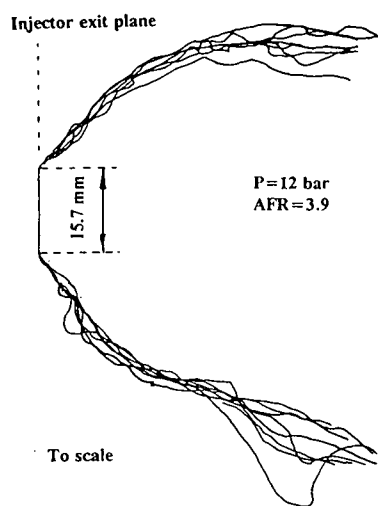


Fig. 3 Measured instantaneous spray profiles

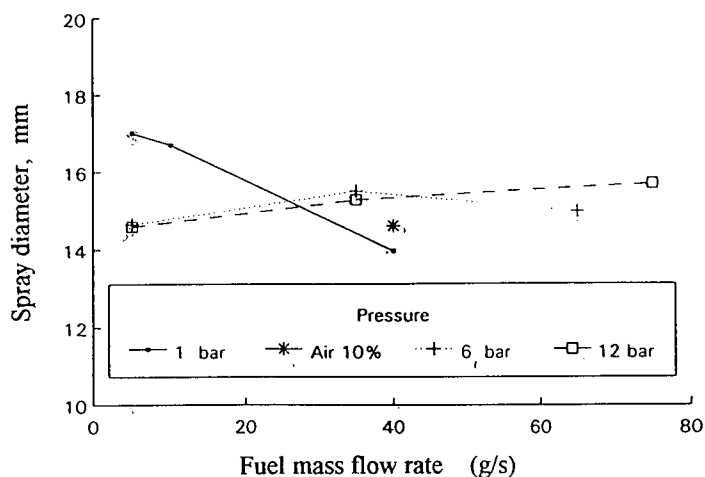


Fig. 6 Variation of spray exit diameter with fuel flow rate

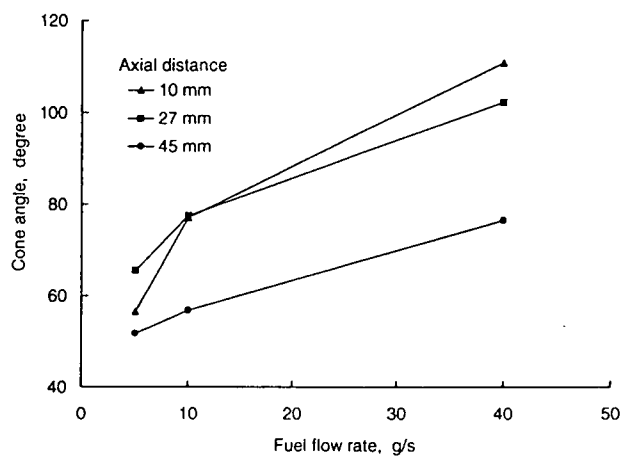


Fig. 4 Effect of fuel flow rate on spray cone angle - 1 bar

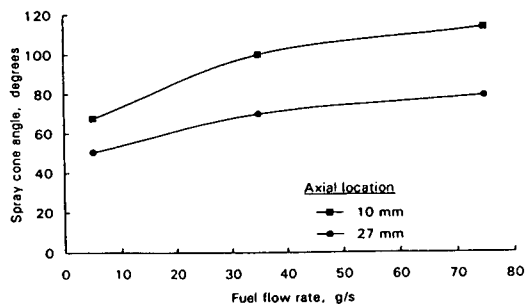


Fig. 5 Effect of fuel flow rate on spray cone angle - 12 bar

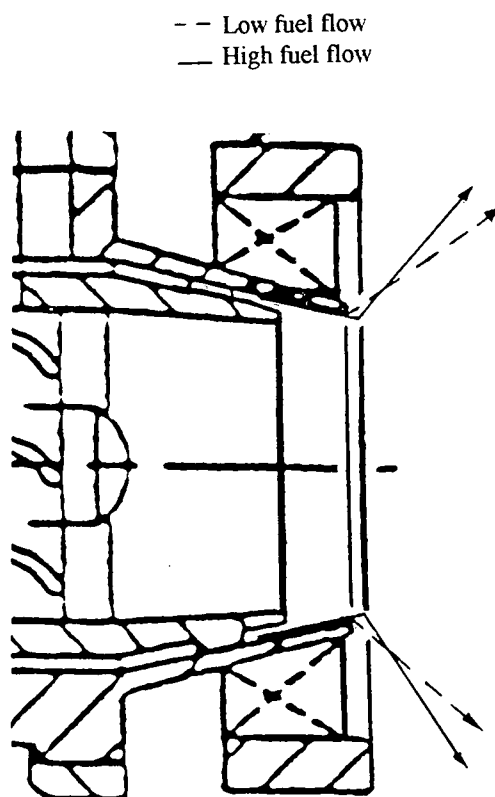


Fig. 7 Effect of momentum on fuel trajectory

Structure of Airblast Sprays Under High Ambient Pressure Conditions

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A single-velocity-component phase Doppler particle analyzer is used to survey and measure local variations in drop-size distributions and drop velocities in the near-nozzle region of a practical, contraswirling, prefilming airblast atomizer. The technique of laser sheet imaging is used to obtain global patterns of the spray. All measurements are taken with a constant pressure drop across the atomizer of 5 percent, at ambient air pressures of 1, 6, and 12 bar. The liquid employed is aviation kerosine at flow rates up to 75 g/s. The results show that increasing the air pressure from 1 to 12 bar at a constant air/fuel ratio causes the initial spray cone angle to widen from 70 to 105 deg. Farther downstream the spray volume remains largely unaffected by variations in atomizer operating conditions. However, the radial distribution of fuel within the spray volume is such that increases in fuel flow rate cause a larger proportion of fuel to be contained in the outer regions of the spray. The effect of ambient pressure on the overall Sauter mean diameter is small. This is attributed to the fact that the rapid disintegration of the fuel sheet produced by the contraswirling air streams ensures that the atomization process is dominated by the "prompt" mechanism. For this mode of liquid breakup, theory predicts that mean drop sizes are independent of air pressure.

Introduction

Originally introduced as a measure to alleviate smoke emissions from turbojet engines, prefilming airblast atomizers are now employed in a wide range of aircraft, industrial, and marine gas turbines. A key feature of all practical prefilming airblast atomizers is that the bulk fuel is first spread into a thin continuous sheet, a process called "prefilming," and then exposed to high-velocity, swirling air streams on both sides of the sheet.

In recent years considerable advances have been made in the development of laser diagnostic techniques for spray characterization. These developments have led to a resurgence of interest in determining the properties of sprays produced in prefilming airblast atomization. Efforts are now under way to gain a better understanding of the basic phenomena occurring within complex practical systems of the types currently in service on advanced turbojet engines. Wang et al. (1992a, 1992b, 1994, 1995) and McDonnell et al. (1994) used two-component phase-Doppler interferometry to make detailed measurements in the flows downstream of a SNECMA/General Electric CFM-56 airblast atomizer. In addition to time-averaged properties, transient phenomena were also examined. These studies provided valuable insight into the general structure of the gas phase as well as details regarding the complex behavior of drops. Of special interest from a practical viewpoint is that actual engine hardware was used to examine the sensitivity of the spray structure to scaling and hardware variations. Hebrard et al. (1991, 1993) also used two-component phase-Doppler interferometry to characterize the two-phase flow field generated by an engine airblast atomizer. Their measurements included mean axial and transverse velocities for each phase as well as volume flux and drop size distributions. Wynne and Jasuja (1991) and Jasuja and Lefebvre (1994) used various nonintrusive techniques, including phase-Doppler interferometry, high-intensity spark pho-

tography, high-speed cinephotography, video imaging to capture the dynamic and unsteady spray characteristics produced in prefilming airblast atomization. All the injectors used in the program were typical of modern gas turbine practice and differed from each other only with regard to various design details, such as swirler flow area and vane angle. The results obtained showed that the sprays produced by actual engine nozzles exhibit appreciable nonuniformities with regard to droplet trajectories and mass flux distributions. In our 1994 study, all measurements of spray characteristics were carried out at distances of 50 to 70 mm downstream of the fuel nozzle. The objective of the present work is to extend the previous study by carrying out detailed mapping of drop size distributions and drop velocities at higher fuel throughputs and in regions closer to the nozzle. This near-nozzle region is of special importance from a combustion viewpoint because it is the zone in which combustion is initiated and sustained.

Experimental

The test facility for this study is a large cylindrical vessel designed to operate at high pressures in accordance with British Standards specification BS 5500. A flexible optical window arrangement permits the use of nonintrusive diagnostics, including phase-Doppler interferometry and laser sheet imaging. High-pressure air is delivered from a multistage screw-type compressor to the fuel injector, which is located at one end of the test vessel and is arranged to spray horizontally along its major axis, as shown schematically in Fig. 1. The same source of air is used to pressurize the test vessel, the level of pressure being controlled by means of a spill valve, which is located at the downstream end of the vessel.

Atomizer. The fuel injector is essentially a prefilming airblast atomizer of the type shown in Fig. 2 which is representative of the injectors used in many gas turbine combustors. It features a pair of concentric air inlets that generate two separate swirling airflows in opposite directions. Low-velocity fuel is first spread into a thin, circumferentially uniform sheet on an annular surface and then sandwiched between the two swirling

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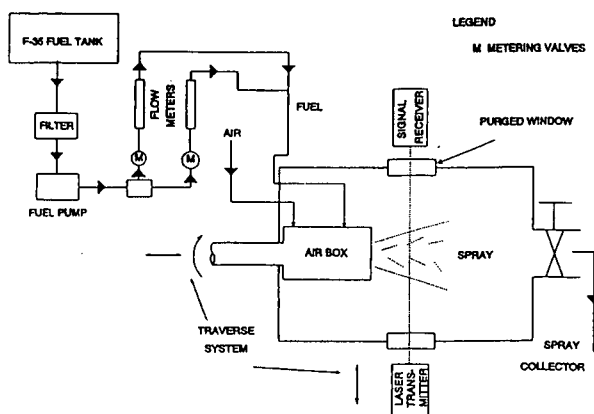


Fig. 1 High-pressure spray facility

air streams. This configuration promotes a high shearing action between the fuel and the atomizing air, which is beneficial to atomization and also helps to match the resulting spray with the combustor air flow pattern. The fuel injector is fitted into a high-pressure air box located inside the test vessel, as shown in Fig. 1.

Two separate and independent traverse systems for the air box-fuel injector assembly are provided. The traverse system for the laser diagnostics is a mechanical one offering three degrees of freedom. Normally, the optical system moves along the horizontal diameter of the pressure vessel. The repeatability of positioning is within 0.25 mm. The second traverse system provides two degrees of freedom for the air box relative to the diagnostics line of sight. The first one is a linear movement along the longitudinal axis of the pressure vessel, while the second is a rotational movement around the axis of the air box. As both of these movements are controlled by a computer-operated stepper motor, very precise and repeatable injector positioning can be achieved.

Optical Diagnostics. Four optical-quality quartz windows provide the desired optical access into the pressure vessel. Each of these large windows has a multipoint purge feed of high velocity air to prevent fuel deposition. A single-component phase-Doppler particle analyzer (PDPA), manufactured by Aerometrics Inc., was used in this study. Its velocity component coincides with the main axis of the conical sprays. The instrument was operated in the forward scattering mode, which is best suited for dense spray measurements. Its argon-ion laser gave a maximum power in the probe volume of around 250 mW at a wavelength of 514.5 nm. During the course of the investigation, special attention was paid to the setting up and operation of the PDPA, in particular, the laser power and the photomultiplier tube (PMT) voltage. The methods employed to optimize data quality have been described in some detail by Jasuja and Lefebvre (1994). The FFT-type signal processor—a Doppler Signal Analyzer (DSA)—used in the measurements is claimed to be capable of processing signals as weak as -5 db (Zhu et al. 1993).

The technique of laser sheet imaging was also applied to obtain global patterns of the spray. With this technique, a pulsed Nd:YAG laser beam is converted into the form of a thin sheet, which illuminates the spray flow field under investigation. The system provides a power density of 27 MW/cm² in the laser sheet probing volume. The scattered signals at a wavelength of 532 nm were recorded on black and white film positioned perpendicular to the laser sheet. The laser pulse duration of 15 ns is generally considered short enough to freeze the particle motion. The primary magnification factor (i.e., negative image size to actual object size) is 0.5.

Test Conditions. The test conditions were selected to simulate the air densities encountered in gas turbine combustors when operating at pressures up to 30 bar. All measurements were taken with a pressure drop across the atomizer, $\Delta P/P$, of 0.05, i.e., 5 percent, which is typical of modern combustors. Atomizer air/fuel ratios ranged from 1.1 to 7.8. The ambient air temperature was kept constant at around 323 K. The ambient air pressures employed were 1, 6, and 12 bar. Air flow rates were measured using an orifice plate meter. A rotameter/turbine flow meter combination was used to measure fuel flow rates. At the 12 bar condition, the maximum air and fuel mass flow rates were 0.3 kg/s and 75 g/s, respectively. Aviation kerosine ($\mu = 0.0013$ kg/ms, $\sigma = 0.0277$ kg/s², and $\rho = 784$ kg/m³, all at 288 K) was used throughout the test program. PDPA data were taken at downstream distances from the atomizer exit plane of 27 and 45 mm along radii perpendicular to the spray axis. Due to the signal attenuation associated with high throughput sprays, when operating at a pressure of 12 bar the sample size was reduced from 5000 to around 2000 drops to avoid long run times.

Results

One phase of the test program was devoted to photographic studies using pulsed laser sheet lighting to illuminate the spray. The main objective was to examine the extent to which the overall size and shape of the spray are affected by changes in pressure and fuel flow rate. Such information could lead to a better understanding of the effects of these parameters on various aspects of combustion performance. Knowledge of global spray dimensions over a range of atomizer flow conditions provides useful guidance in determining the optimum locations within the spray (in terms of downstream distance and spray radius) for the measurements of drop size and velocity distributions during the PDPA investigation phase.

Spray Structure. Some of the results of the photographic studies are shown in Figs. 3 and 4. Figure 3 shows how the physical structure of the spray is affected by an increase in ambient air pressure from 1 to 12 bar while maintaining the fuel mass flow, m_F , constant at 5 g/s. These photographs show clearly the heterogeneous nature of the spray, especially at low air pressures.

Inspection of these and other photographs, along with corresponding measurements of drop velocities, suggests that the annular sheet of fuel flowing over the prefilmer lip rapidly disintegrates into droplets, which tend to maintain the general direction imparted to the air by the air swirlers incorporated within the atomizer. However, as the atomizing-air flow field expands downstream of the nozzle, the combined effects of aerodynamic diffusion and external air entrainment cause veloc-

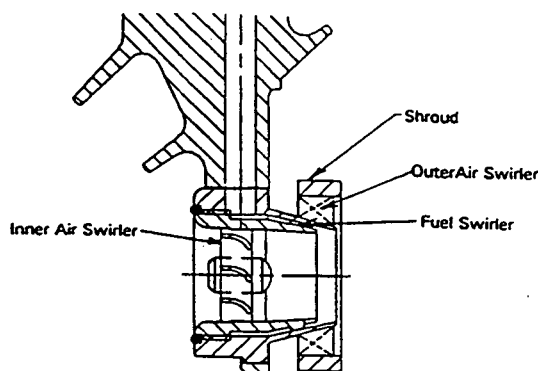


Fig. 2 Schematic diagram of airblast atomizer (courtesy of Parker Hannifin Corp.)



Fig. 3 Influence of air pressure on spray structure for a constant fuel flow; $m_F = 5 \text{ g/s}$

ities to decline. This is especially true in the outer regions of the spray where the effects of air entrainment are most pronounced.

In most practical combustors, the fuel flow does not remain constant as pressure is varied, but rather changes in such a manner as to maintain a fairly constant air/fuel ratio (AFR). Figure 4 shows similar photographs to those presented in Fig. 3 except that for these tests the fuel flow was increased along with pressure to provide a constant AFR of 3.9. These photographs show the spray emerging from the nozzle and then expanding radially outward to form a hollow-cone spray. As the droplets move downstream, the spray boundaries, which initially are in the form of a straight cone, start to become curved due to the effects of air interaction, as mentioned earlier. Measurements of spray profiles are made difficult by the fact that the eddies generated by the shearing action of the two contrarotating swirling air flows cause the spray boundaries to fluctuate. Inspection of Figs. 3 and 4 suggests the possible occurrence of periodicity in the flow near the atomizer. Clearly this aspect warrants further investigation, since any pulsatile behavior in this region could give rise to combustion instability, although none has been experienced with this type of atomizer. In this context it is worth recalling that the eddy shedding associated with many types of bluff-body flame holders under cold-flow conditions is no longer observed under burning conditions. By superimposing on each other a number of spray profiles derived from individual high-speed photographs, as illustrated in Fig. 5 for a pressure of 1 bar and an AFR of 3.9, an informative and reasonably accurate "mean" spray profile can be constructed.

The fact that the sprays produced in airblast atomization tend to have curved boundaries creates difficulties in the definition and measurement of cone angle. With pressure-swirl atomizers, this problem is usually resolved by defining the cone angle as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the atomizer face. For prefilming airblast atomizers, an analogous method would be to use straight lines drawn from the prefilming lip to intersect the spray boundaries at some specified distance downstream of the lip. A drawback to this approach, at least in the context of the contraswirler design employed in these experiments, is that the diameter of the spray as it emerges from the nozzle is not only different from that of the prefilmer but also varies with changes in atomizer operating conditions. Measurements of spray diameter just downstream of the nozzle exit plane yielded values of 17.6, 15.5, and 15.7 mm for pressures of 1, 6, and 12 bar, respectively. For these measurements the AFR was held constant at 3.9. The cone angles obtained by drawing straight lines from the spray diameter at the nozzle exit to the mean spray diameter at certain specified distances downstream of the nozzle are presented in Fig. 6. They show that in the "near-nozzle" region, where the influence of the "natural" spray cone angle (i.e., the cone angle without any air flow) is quite strong, the cone angle widens with an increase in air pressure at a constant AFR. This is because the natural cone angle of the spray is wider than the cone angle of the atomizing air and its contribution to the resultant spray angle increases as a result of the increase in fuel/air

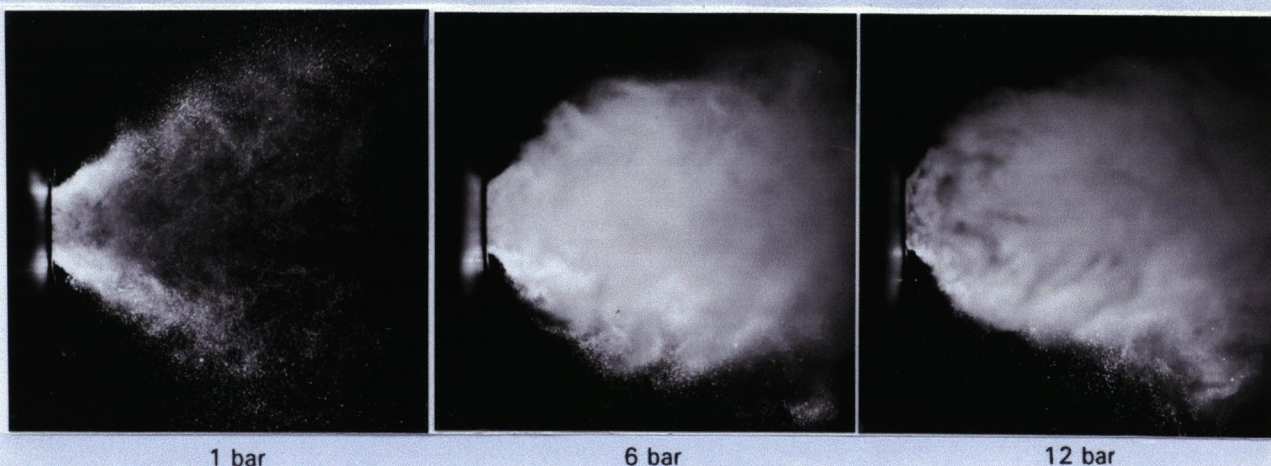


Fig. 4 Influence of air pressure on spray structure for a constant air/fuel ratio; AFR = 3.9

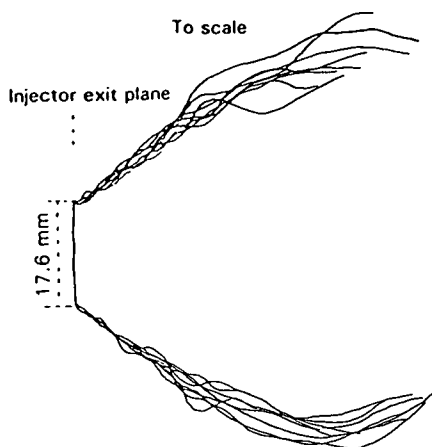


Fig. 5 Spray profiles measured at $P = 1$ bar and $AFR = 3.9$

momentum ratio that accompanies an increase in air pressure at constant AFR. Farther downstream, where atomization is complete and the droplets are completely airborne, the spray angle becomes largely independent of pressure. This result is only to be expected since the swirling and recirculating air flow patterns created by the air swirlers are independent of air pressure. However, it is important to recognize that although the overall dimensions of the aerodynamic recirculation zone tend to remain fairly constant with changes in operating conditions, the radial distribution of fuel within the total spray volume does vary with changes in pressure and fuel flow rate. This is illustrated in Fig. 7, which shows that increases in m_F tend to place more fuel in the outer regions of the spray. Photographic images such as those presented in Figs. 3 and 4 provide valuable insight into the prevailing spray structures, but caution must be exercised in their interpretation. For example they do not yield reliable information regarding such important spray properties as the size, velocity, and number density of droplets.

Drop Size and Velocity Distributions. The effects of variations in fuel flow rate on the radial distribution of Sauter mean diameter (SMD) and droplet velocity are demonstrated in Fig. 7 for values of m_F of 35, 50, and 65 g/s at a constant air pressure of 6 bar. As might be expected, increase in fuel flow rate increases both the local values of SMD and the overall spray SMD (SMD). The latter was obtained as the mean of all the local measured values after each local value had been corrected using appropriate area and velocity weighting factors to account for the higher flow areas in the outer regions of the spray and the nonuniformity of the radial velocity distribution.

Figure 8 illustrates the results of detailed spray measurements carried out at normal atmospheric pressure. In this figure, local measured values of SMD and mean axial velocity are shown plotted against radial distance from the centreline of the spray. Measurements were carried out in two planes at downstream distances, Z , of 27 and 45 mm. The fuel flow rate was adjusted to maintain a constant AFR of 3.9.

The SMD curves shown in Fig. 8 are typical of all the results obtained at atmospheric pressure. At $Z = 27$ mm, the SMD initially increases with increase in spray radius up to a maximum value, which usually occurs at about the midradius, and then declines to a fairly constant value of SMD throughout the outer regions of the spray where most of the drops are located. With increase in downstream distance, the flow recirculations and mixing processes evident in Fig. 3 cause the radial distributions of both SMD and axial velocity to become more uniform. Thus, at a downstream distance of 45 mm, the local values of SMD increase gradually and continuously with increase in spray radius, as shown in Fig. 8.

Conversion of the local SMD values in Fig. 8 to $\overline{SMD}$ data revealed virtually no differences in SMD between the measurements carried out at downstream distances of 27 and 45 mm, being 54 μm in one case and 55 μm in the other. This suggests that the atomization process is virtually complete within a distance of 27 mm from the atomizer exit. It also indicates that in the fairly dilute sprays associated with atomization at low air pressures and low fuel flows rates, the effects of droplet coalescence, if any, are negligibly small. This is supported by the relatively flat droplet size-velocity correlation observed at this condition, thus implying no significant difference between the mean velocities of different drop size classes. The droplet velocities presented in Fig. 8 largely reflect the local values of axial air velocity. Near the spray axis, axial velocities are low and sometimes negative due to reverse flow of air in this region resulting from the large-scale flow recirculations created by the atomizing air. In the outer regions of the spray, the entrainment of surrounding air inevitably leads to a reduction in axial velocity, with the result that droplet velocities tend to be highest at about the midradius of the spray.

Figure 9 shows similar data to those presented in Fig. 8 for a pressure of 6 bar. At this higher ambient pressure the local values of SMD are fairly constant throughout the spray volume, increasing slightly with increase in spray radius. There is also a small rise in SMD from 47 to 50 μm with increase in Z from 27 to 45 mm. Other measurements at 6 bar showed similar small increases in SMD with increase in downstream distance, but the total number of data points obtained was too small to draw any worthwhile conclusions regarding the possible intervention of drop coalescence. Additional measurements at much higher pressures might have proved instructive in this regard. Unfortunately, at a pressure of 12 bar the spray density was usually too high to permit accurate measurements of SMD at $Z = 27$ mm. Consequently, the only data acquired at this pressure were at a downstream distance of 45 mm.

The influence of ambient air pressure on SMD is shown more directly in Fig. 10. These data indicate that an increase in pressure serves to reduce the SMD. The effect is not large. For the test conditions quoted on the figure, SMD is reduced from 55 to 38 μm by an increase in pressure from 1 to 12 bar. Even this small effect of pressure is exaggerated by the fact that in these tests the fuel flow rate was maintained constant at 35 g/s regardless of changes in air pressure. Other tests in which pressure was varied while maintaining a fairly constant AFR, showed a much smaller effect of pressure on SMD.

Data Analysis. Analysis of all the experimental data on SMD confirmed that the effect of pressure was small and could be described by the relationship $SMD \propto P^{-0.05}$. The analysis

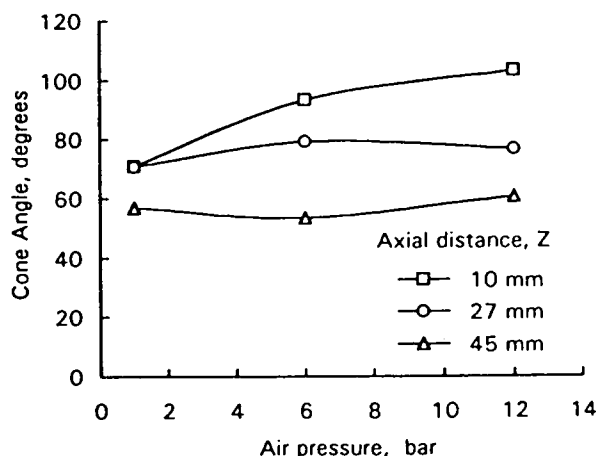


Fig. 6 Influence of pressure on spray cone angle for $AFR = 3.9$

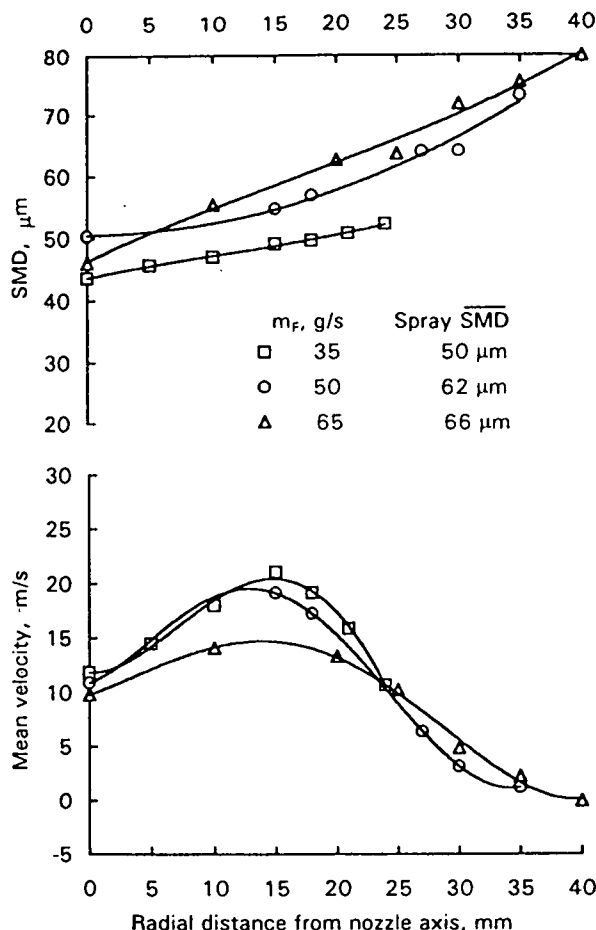


Fig. 7 Influence of fuel flow rate on drop sizes and velocities at $P = 6$ bar and $Z = 45$ mm

also indicated that the main factor governing spray $\overline{SMD}$ is air/fuel ratio, as indicated in the following empirical equation for $\overline{SMD}$ used to provide the data correlation shown in Fig. 11:

$$\overline{SMD} = 48 P^{-0.05} (1 + AFR^{-1})^{0.5}$$

where $\overline{SMD}$ is in microns and P is the ambient air pressure in bar. This equation has no basic significance and is not dimensionally correct but it serves to illustrate the effects on mean drop size of the two main parameters covered in this investigation, namely air/fuel ratio and pressure. The air/fuel ratio term presents no special problems because the relationship $\overline{SMD} \propto (1 + AFR^{-1})^{0.5}$ has been reported by several previous workers, including Wigg (1964) and Jasuja (1979). Of primary concern is the relatively small effect of pressure on $\overline{SMD}$. Previous studies at Cranfield by Jasuja (1981, 1982), El Shanawany and Lefebvre (1980), and Rizk and Lefebvre (1984) yielded pressure exponents ranging from -0.4 to -1.0 . A possible explanation for the apparent discrepancy between these results and those obtained in the present investigation is that airblast atomization can occur by one or two different mechanisms, or sometimes by a combination of both. If the atomizing air is flowing in generally the same direction as the fuel, atomization takes place relatively slowly by the classical mechanisms of liquid sheet breakup whereby $\overline{SMD}$ decreases markedly with increase in ambient air pressure (Squire, 1953). However, if sheet breakup occurs rapidly, the flow and surface instabilities that are an essential prerequisite for the classical mechanism of

breakup have insufficient time to develop. Instead, the fuel sheet disintegrates into droplets as soon as it encounters the atomizing air. Under these conditions of "prompt" atomization, the $\overline{SMD}$ is predicted to be independent of pressure (Lefebvre, 1992). The importance of these findings in the present context is that the previous Cranfield studies were conducted on airblast atomizers in which the liquid and atomizing air were essentially coflowing. This arrangement is characterized by a relatively small aerodynamic interaction between the fuel and the air in the initial stages of the atomization process, thereby providing ideal conditions for breakup to occur via the classical mechanism. On the other hand, with modern practical atomizers (including the fuel injector used in this test program) the fuel sheet is subjected to the strong shear forces generated at the interface between two contraswirling air streams. Under these conditions the prompt mechanism of atomization must necessarily be dominant. This serves to explain why previous results on comparatively low-shear coflowing devices exhibited a marked dependence of $\overline{SMD}$ on pressure, whereas more recent measurements on modern high-shear practical atomizers generally indicate a much lower dependence of $\overline{SMD}$ on pressure.

Measurements reported by Jasuja and Lefebvre (1994) on a SNECMA prefilming airblast atomizer showed that with this nozzle design the $\overline{SMD}$ actually increased slightly with increase in pressure. They attributed this result to a combination of several possible effects, all of which are related to the increase in fuel flow rate that accompanies an increase in air pressure at

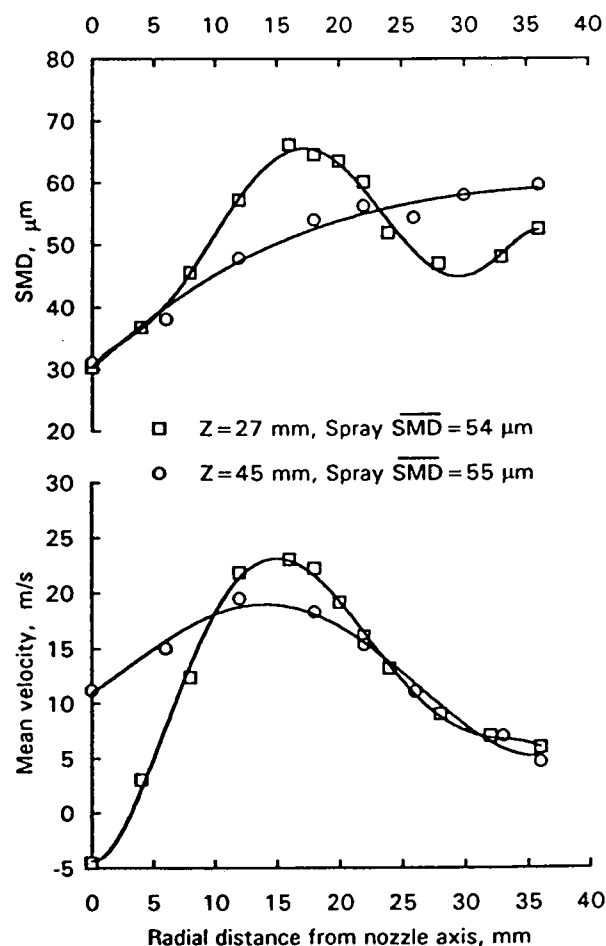


Fig. 8 Influence of downstream distance on drop sizes and velocities; $P = 1$ bar and $AFR = 3.9$

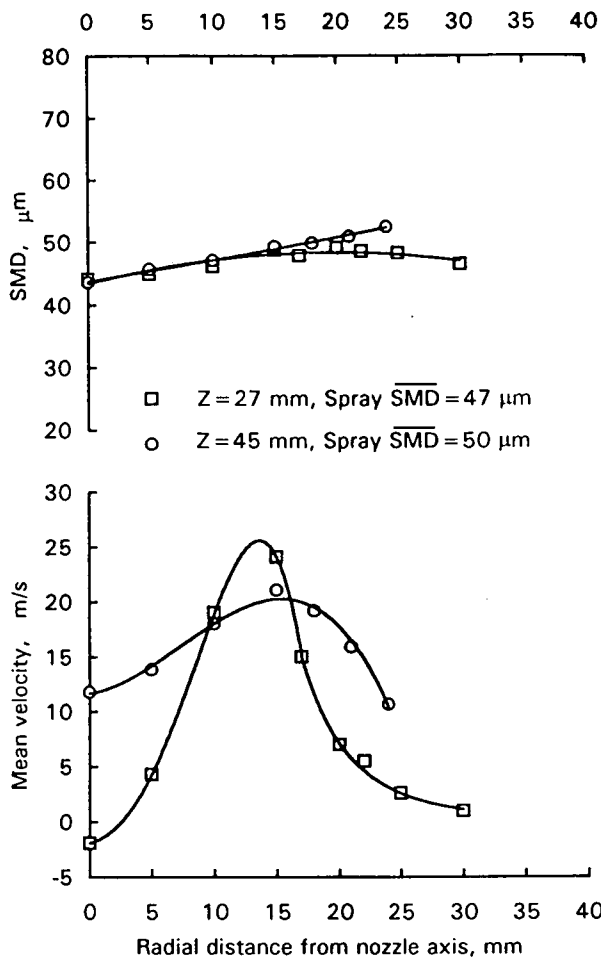


Fig. 9 Influence of downstream distance on drop sizes and velocities; $P = 6$ bar and AFR = 3.9

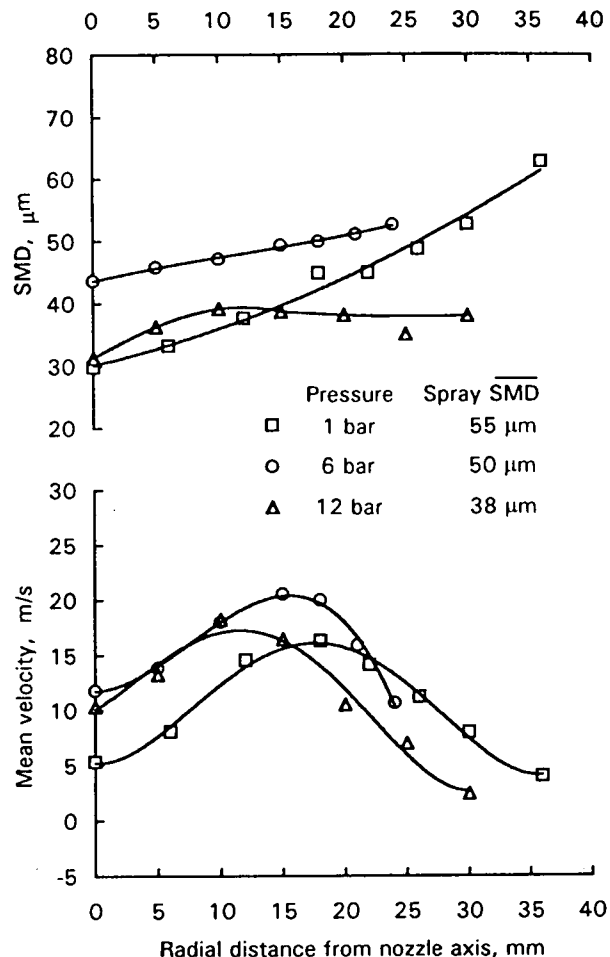


Fig. 10 Influence of air pressure on drop sizes and velocities; $Z = 45$ mm and $m_f = 35$ g/s

constant AFR. These include increase in initial film thickness, reduction in relative velocity between the fuel and the atomizing air, increased droplet coalescence, and the lower accessibility of the fuel to the atomizing air.

The fact that some or all of these effects can contribute toward increasing the SMD was confirmed in the present investigation, in which a number of tests were carried out at different levels of pressure while maintaining either a constant fuel flow rate (by allowing the AFR to increase linearly with increase in pressure) or a constant AFR. The purpose of these tests was to enable the effect of fuel flow rate on SMD to be separated from that of pressure. The results showed that increasing the pressure from 1 to 6 and then to 12 bar, while maintaining the fuel flow constant at 35 g/s, caused the measured SMD to decline from 55 to 50 and then to 38 microns, as shown in Fig. 10. This relatively large reduction in SMD ($SMD \propto P^{-0.15}$) is due mainly to the increase in AFR that accompanied the increase in pressure. Similar tests over the same range of pressures for a constant AFR of 3.9 revealed a much smaller pressure dependence ($SMD \propto P^{-0.05}$). These findings when considered alongside those obtained on a different design of prefilming airblast atomizer by Jasuja and Lefebvre (1994) tend to suggest that for high-shear atomizers the influence of pressure per se on overall Sauter mean diameter is quite small. In practice, increase in pressure may cause the SMD to either increase slightly or decrease slightly, depending on the design of the atomizer that governs the nature of the ensuing interaction between the fuel

and the air streams. Clearly, a more systematic investigation is warranted to explore more fully the manner and extent to which various atomizer design features, notably prefilmer and air swirl geometries, govern the influence of air pressure on overall spray mean drop size.

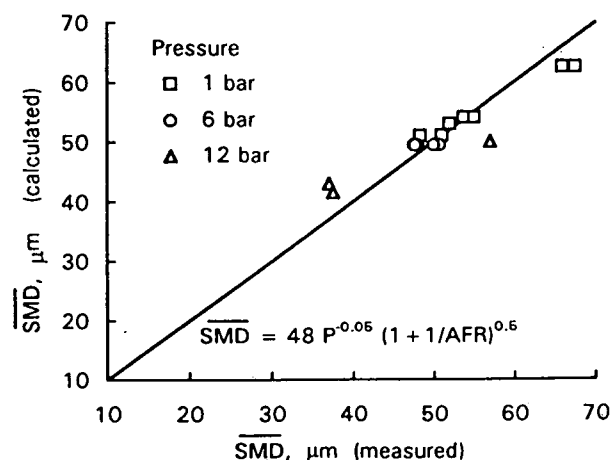


Fig. 11 Correlation of SMD data

Conclusions

From a series of measurements of drop sizes, drop velocities, and spray profiles carried out using kerosine fuel on a modern, practical, prefilming airblast atomizer featuring contraswirling air flows, the following conclusions are drawn:

1 Increase in ambient air pressure at a constant air/fuel ratio causes the initial spray cone angle to widen from 70 deg at 1 bar to around 105 deg at 12 bar. Farther downstream the cone angle and overall dimensions of the spray volume tend to remain fairly constant and independent of pressure.

2 The radial distribution of fuel within the spray volume is such that increase in fuel flow rate and/or decreases in air pressure cause a larger proportion of fuel to be contained in the outer regions of the spray.

3 Near the spray axis, the droplet axial velocities are generally low and sometimes negative. Droplet velocities increase with increase in spray radius, usually attaining their maximum values around the midradius of the spray. Beyond this point, velocities decline with increase in radius, reaching minimum values at the spray boundaries. This decline in axial velocity is attributed to the decelerating effect of air entrainment into the outer regions of the spray.

4 The results of tests carried out over a range of pressures from 1 to 12 bar show that the effect of ambient air pressure on the overall Sauter mean diameter (SMD) of the spray is quite small. This is attributed to the fact that for contraswirling airblast atomizers of the type employed in this investigation, the atomization process is dominated by the prompt mechanism of liquid sheet breakup, which theory indicates should be independent of pressure.

Acknowledgments

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INFLUENCE OF AMBIENT AIR PRESSURE ON PRESSURE-SWIRL ATOMIZER SPRAY CHARACTERISTICS

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ABSTRACT

A single-component PDPA is used to evaluate the spray characteristics of a simplex pressure-swirl atomizer when operating at high liquid flow rates and elevated ambient air pressures. Attention is focused on the effects of air pressure on mean drop size, drop-size distribution, mean velocity, volume flux, and number density. Using a constant flow rate of 75 g/s, measurements are carried out along the spray radii at a fixed distance downstream from the atomizer face of 50 mm. The air pressures of 1, 8, and 12 bars chosen for these tests correspond to air densities of 1.2, 9.6, and 14.4 kg/m³. The purpose of the investigation is to supplement the existing body of information on pressure-swirl spray characteristics, most of which were obtained at normal atmospheric ambient pressures, with new data that correspond more closely to the conditions prevailing in the primary combustion zones of modern gas turbines. The results obtained are explained mainly in terms of the influence of air pressure on spray structure, in particular spray cone angle and Weber number.

INTRODUCTION

The continuous increase in engine pressure ratios from around 7 to 10 in the early 1950's to around 20 in the late 1960's brought to light a basic defect of all forms of pressure-swirl atomizer, namely an innate tendency to produce copious amounts of soot and smoke at high combustion pressures. These considerations led to the development of the prefilming airblast atomizer, which exhibited such overwhelming advantages over pressure-swirl nozzles in terms of reduced pollutant emissions and

improved pattern factor, that by 1970 it was universally accepted as the fuel injector of choice for advanced gas turbines of high pressure-ratio. However, this did not mark the end of pressure-swirl nozzles for gas turbine applications. Operating experience soon showed that combustors fitted with airblast atomizers are characterized by narrow stability limits at all power settings and generally unsatisfactory combustion performance at those operating conditions which correspond to low atomizing air velocity such as, for example, engine startup. It was found that these problems could be overcome, albeit at some additional cost and complexity, by combining a simplex pressure-swirl nozzle with an airblast atomizer to form what is generally known as a "piloted" airblast atomizer, or "hybrid" injector. This combination provides easy light-up and wide stability limits along with all the performance advantages offered by prefilming airblast atomizers at high power conditions.

Pressure-swirl atomizers are also used as a means of delivering fuel onto a prefilming surface within a swirl cup arrangement featuring contra-rotating airflows as, for example, in the SNECMA/GE CFM-56 engine. Considerable interest is now being shown in the airblast simplex, or "ABS" atomizer, which comprises a simplex pressure-swirl nozzle surrounded by a co-flowing stream of swirling air [1]. Yet another recent application of pressure-swirl atomizers is to ultra-low NO_x combustors. In some low-NO_x designs a simplex nozzle is used as a piloting device for the main combustion process which takes place downstream at extremely fuel-lean conditions.

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Despite these and other important applications of pressure-swirl atomizers, our knowledge of their spray characteristics is far from satisfactory, especially at conditions corresponding to high combustion pressures. A main purpose of this study is to examine the influence of ambient air pressure on the radial distribution of drop-sizes within high-throughput, dense sprays of the type produced by pressure-swirl atomizers when fitted to gas turbine engines of high compression ratio. A further objective is to provide experimental data on other important spray characteristics for use in combustor modeling. To the best of the authors' knowledge, no other pressure-swirl nozzle performance data exist in the literature for such extreme conditions of liquid throughput (75 g/s) and high ambient air pressure (12 bars).

EXPERIMENTS

The test facility for this study has been described in detail elsewhere [2]. Its main component is a large cylindrical vessel that can be supplied with high-pressure air at near-ambient temperature to achieve the desired level of pressure. The atomizer is located at one end of the vessel and is arranged to spray horizontally along its major axis. Four large quartz windows provide optical access to the spray. Each of these windows has a multi-point purge feed of high velocity air to prevent fuel deposition. PDPA data are normally taken with the instrument operating in the forward scattering mode, along radii perpendicular to the spray axis at a fixed downstream distance from the atomizer exit plane.

The hollow-cone simplex atomizer employed in these experiments was supplied by Spraying Systems Limited and featured the orifice insert SIY48 and orifice SKY27 with a discharge hole diameter of 1.93 mm. According to the manufacturer, nominal cone angle of the developed spray under atmospheric air pressure conditions was 83° . Flow number, FN, was calculated to be $0.124 \times 10^{-3} \text{ m}^3/\text{hr}/\text{Pa}^{0.5}$ (22.75 pph/psid^{0.5} units). The nozzle was arranged to spray water into quiescent air at pressure levels of 1, 8, and 12 bars. The pressure drop across the atomizer was held constant at 49 bars, regardless of variations in ambient air pressure, to provide a constant water flow rate of 75 g/s. Both PDPA data collection and experimental spray cone angle determination were carried out at a distance of 50 mm downstream of the atomizer. This distance was chosen because it provided ample time for the completion of secondary atomization while avoiding the measurement inaccuracies that can occur in regions further downstream due to excessive spray evaporation. As the outer boundaries of the spray vary with changes in operating conditions, their location was broadly determined for each PDPA traverse using conventional still photographic techniques.

RESULTS AND DISCUSSION

The spray properties of most relevance to continuous-flow combustion processes are mean drop size, drop-size distribution, mean velocity, volume flux, and number density. The results obtained on the effects of ambient air pressure on these properties are discussed below in turn.

Mean Drop Size

Most previous experimental studies on spray characteristics have focused on mean drop size. Usually, some form of light diffraction technique was used and the results were generally expressed in terms of SMD (Sauter Mean Diameter). By and large, the data obtained by different workers exhibit reasonable consistency, one notable exception being the results obtained on the influence of ambient air pressure on SMD. The relationship between mean drop size and air pressure is normally expressed as $\text{SMD} \propto P_A^n$, with reported values of n ranging from +0.27 [3] to -0.53 [4]. Other workers [5, 6] have reported SMD (or D_{32}) increasing with increase in air pressure up to a maximum value and then declining with any further increase in pressure. The observations of Wang and Lefebvre [5], Lefebvre [7], Dodge and Biaglow [4] and Jasuja [8] tend to suggest that these seemingly contradictory results could derive from the rather complex manner in which a change in air density affects Weber number and spray cone angle, and hence also the SMD.

For liquids of low viscosity, the mean drop sizes produced by the disintegration of a liquid sheet may be expressed in dimensionless form as [5,7]

$$\text{SMD}/t_L \propto (We) \propto (U_R^2 \rho_A t_L / \sigma)^x \quad (1)$$

or, for any given liquid,

$$\text{SMD} \propto t_L^{(1-x)} (U_R^2 \rho_A)^x \quad (2)$$

where U_R is the relative velocity between the disintegrating liquid sheet and the ambient air, t_L is the sheet thickness at breakup, ρ_A is the ambient air density, and σ is the liquid surface tension. The value of x must be determined experimentally and is typically around 0.5.

Reference to Eq. (2) shows that an increase in ρ_A should reduce the SMD. However, an increase in ρ_A is usually accompanied by a reduction in U_R and sometimes also by an increase in t_L . Both of these effects tend to increase the SMD. Thus, in any given situation, and depending on liquid properties and atomizer design features, a change in ρ_A (or P_A) may serve either to raise or lower the mean drop size in the spray. These aspects are discussed below.

If increase in air density had little or no effect on spray dimensions, it would serve only to raise We and thereby reduce SMD. However, it has been known since De Corso and Kemeny [9], and more recently confirmed by

Parsons and Jasuja [10], that an increase in P_A above the normal atmospheric value creates radially inflowing air currents that can markedly reduce the spray cone angle. With continuous increase in P_A , the cone angle eventually reaches a minimum value beyond which any further increase in P_A has no effect on cone angle. According to De Corso [11] and Neya and Sato [3] this contraction in spray angle results in increased droplet coalescence, which accounts for their observed increase in SMD with increase in air density. However, a further adverse effect of a reduction in spray angle with increase in P_A is that it reduces the volume of air contained within the spray. In consequence, the momentum of the spray is able to accelerate this smaller volume of air more rapidly in the direction of spray motion, thereby reducing U_R [6]. Neya and Sato also pointed out that with increasing p_A sheet breakup starts closer to the nozzle. Thus, at higher air densities the disintegration process occurs in a thicker sheet, thereby producing larger drops.

Experimental studies on hollow-cone sprays show SMD increasing with P_A until a critical value is reached beyond which any further increase in P_A has little or no effect on SMD. This critical value of P_A is governed by the combined influence of two separate pressure-dependent phenomena, both having their own critical values of P_A . One is the pressure at which the spray cone angle attains its minimum value, and the other is the pressure at which sheet breakup starts directly at the nozzle exit. Clearly, once this condition is reached any further increase in air pressure cannot serve to increase the initial sheet thickness.

In theory, any increase in P_A above the critical value should cause the SMD to decline. However, although the spray angle remains constant at its minimum value, the spray continues to shrink in size due to its reduced axial penetration [12]. This reduction in spray volume reduces U_R , as discussed above, and also promotes droplet coalescence, both of which tend to offset the beneficial effect of increasing P_A in reducing SMD.

The results obtained in the present study on the effect of air pressure on overall spray SMD are plotted in Fig. 1. The values presented in this figure were obtained as the mean of all the local measured values of SMD after each local value had been corrected using appropriate area and velocity weighting factors to account for the larger flow areas in the outer regions of the spray and the non-uniformity of the radial velocity distribution. Figure 1 shows the overall spray SMD increasing with increase in P_A , with the rate of increase in SMD declining at the higher levels of P_A . The general shape of the curve is consistent with the views expressed above in regard to the influence of spray angle on SMD. Spray photographs show that increasing the ambient air pressure from 1 to 8 bars, and then to 12 bars causes the spray angle to change from 71° to 47° and then to 41° . Figure 2 shows the measured local values of SMD, plotted against radial

distance from the spray axis, for all three values of ambient air pressure.

Although all the droplets produced in pressure-swirl atomization have the same initial velocity, the actual value depending on the pressure drop across the atomizer and the internal pressure losses, the larger drops formed in atomization move further away from the atomizer than the smaller drops due to their higher momentum/drag ratio. In consequence, the larger drops tend to be concentrated in the outer boundaries of the spray, as illustrated in Fig. 2. The same air currents that are generated by the ejector action of the spray and which are responsible for the reduction in spray angle, as discussed above, also convey droplets from the outer regions of the spray toward the spray axis. Due to their lower aerodynamic drag, the smaller droplets are preferentially transported while the larger drops tend to remain in the main body of the spray. The end result of this drop-size separation process is that plots of local SMD versus radial distance from the spray axis all tend to have the characteristic shape shown in Fig. 2. This figure shows, for all three levels of pressure, that the smallest drops are mainly confined to the central core of the spray, while the largest drops are located in the outer regions of the spray. Although the small droplets represent only a tiny fraction of the total mass of fuel in the spray, their presence within the spray cone is undesirable because in combustors featuring pressure-swirl fuel nozzles this is a major soot-forming zone [7].

Drop Size Distributions

In common with all other practical atomizers, pressure-swirl nozzles produce a fairly wide spectrum of drop sizes in the spray. Thus, in addition to mean drop size, at least one other parameter is needed to define the distribution of drop sizes in a spray. Two of the most widely used parameters for describing drop-size distributions are the so-called "representative" diameters $D_{0.1}$ and $D_{0.9}$. $D_{0.1}$ (or $D_{0.9}$) is the drop diameter such that 10% (or 90%) of the total liquid volume is in drops of smaller diameter. Low values of $D_{0.1}$ are highly desirable in aeronautical gas turbines where the presence of small droplets is highly conducive to good combustion performance at high altitudes. Low values of $D_{0.9}$ are beneficial for all types of gas turbines because it is well established that large fuel drops encourage the formation of pollutant emissions. Plots of $D_{0.1}$ and $D_{0.9}$ versus radial distance from the spray axis are presented in Figs. 3 and 4 respectively, for all three levels of pressure. It is evident in these figures that the curves exhibit the same general shape as the curves for SMD, i.e. values are lowest at or near the spray axis and then rise with increase in radial distance to reach a maximum in the outer regions of the spray.

The difference between $D_{0.9}$ and $D_{0.1}$ is sometimes used to indicate the distribution of drop sizes in a spray. When $D_{0.9}-D_{0.1}$ is non-dimensionalized by dividing by $D_{0.5}$,

it is termed the "relative span factor" [13]. A more widely used expression, however, is the Rosin Rammler distribution parameter, q . The higher the value of q , the smaller is the range of drop sizes in the spray. From analysis of the measured drop sizes it was found that for 1 bar the values of q at various radial locations ranged from 2.6 at the spray axis to around 3.1 at the edge of the spray, with an average weighted value of 3.0. This is consistent with previous reported values of q for pressure-swirl atomizers operating at normal atmospheric pressure [5, 14]. The results at 8 bars showed values for q rising from 3.5 in the central core of the spray to around 4.0 at the spray periphery, with an average weighted value of 3.9. Raising the pressure from 8 to 12 bars produced no further significant increase in q . The relatively low value of q for 1 bar, indicating a broader range of drop sizes in the spray than for 8 and 12 bars, is well illustrated in Fig. 2. Inspection of this figure shows that the variation of local SMD values along the spray radius is appreciably wider at 1 bar than at the two higher levels of ambient air pressure.

Drop Velocities

The influence of ambient air pressure on the radial distribution of mean droplet velocity is illustrated in Fig. 5. The instrument used to obtain the results presented in this figure is limited to one component of particle velocity, in this case the velocity component along the main axis of the cylindrical test vessel, which also coincides with the main axis of the conical spray. Because the pressure drop across the atomizer was maintained constant at 49 bars for all values of P_A , the velocity at which the water was discharged from the nozzle was also independent of P_A . With pressure-swirl atomizers the drop sizes in the spray gradually increase with increase in radial distance from the spray axis, as shown in Fig. 2. Due to their higher momentum/drag ratio, the rate of deceleration for large drops is lower than for small drops. This leads to higher drop velocities with an increase in radial distance, as illustrated in Fig. 5, which contains measurements of drop velocity for an ambient air pressure of 1 bar. Only in the outer regions of the spray, where the drops are more exposed to the aerodynamic drag forces created by their interaction with the surrounding quiescent air, is drop velocity observed to decline with increase in radial distance from the spray axis. As these drag forces increase linearly with increase in P_A their influence on droplet deceleration is more pronounced at higher levels of P_A , as illustrated in Fig. 5.

The results contained in Fig. 5 are of special interest and relevance to continuous-flow, high-pressure combustion systems, a notable example being the gas turbine combustor. They show that an increase in combustion pressure leads to a marked decline in droplet velocity and hence also in axial spray momentum. In consequence, at high combustion pressures a much

larger proportion of the fuel drops fail to penetrate beyond the main soot-forming zone that is located just downstream of the fuel nozzle. This leads to high rates of soot production and copious amounts of exhaust smoke, both of which are characteristic of high-pressure ratio gas turbines fitted with pressure-swirl atomizers.

Volume Flux

The data obtained on volume flux are illustrated in Fig. 6. It should be noted that these data, along with those presented in Fig. 7 for number density, are derived quantities and thus their absolute values must be treated with caution. They are included here in order to show trends and provide a more complete description of the spray. Fig. 6 contains information on how the liquid mass flux is distributed radially within the spray volume and the manner in which this distribution is influenced by ambient air pressure variation. Since the liquid flow rate is the same for all values of P_A , it might be expected that the volume flux would also remain fairly constant and independent of P_A . In practice, the volume flux generally increases with increase in air pressure, as shown in Fig. 6. This is because an increase in P_A reduces the cone angle of the spray so that the same amount of liquid now flows through a spray of smaller cross-sectional area. With most pressure-swirl atomizers, the spray cone angle diminishes quite rapidly as the ambient air pressure is raised above its normal atmospheric value. At air pressures above around 5 or 6 bars the rate of spray contraction declines appreciably. These effects of spray contraction on volume flux are well illustrated in Fig. 6, which shows a large difference in the radial distribution of volume flux between 1 and 8 bars and a much smaller difference between 8 and 12 bars. Due to the well-defined, hollow-cone structure of the spray at normal atmospheric pressure, exceptionally high values of volume flux might be expected to occur in the outer regions of the spray, and this is confirmed by the results shown for 1 bar in Fig. 6. With increase in air pressure above 1 bar, the spray starts to lose its "hollow-cone" structure and gradually converts into something more akin to a "solid-cone" spray in which the radial distribution of volume flux is more uniform.

Number Density

The influence of ambient air pressure on the radial distribution of number density is illustrated in Fig. 7. In a symmetrical spray, the number density at any radial distance from the spray axis is governed primarily by the total nozzle liquid flow rate and the radial distributions of volume flux, mean drop size and droplet mean velocity. Thus, in the present case, where the total liquid flow rate remains constant at all operating conditions, the general trends of the results presented in Fig. 7 can be predicted from inspection of the data contained in Figs. 2, 5 and 6. Figure 7 shows that for all air pressures the number

density increases with increase in radial distance from the spray axis. It also reveals that number densities are greatest at the highest level of air pressure. Although the drop sizes are the largest at this condition (see Fig. 2), which by itself should serve to reduce number density, this effect is more than outweighed by the concomitant reduction in spray volume. The lowest values of number density are observed near the centreline of the spray where the volume flux levels are generally low (see Fig. 6).

CONCLUSIONS

From measurements of spray characteristics carried out at ambient air pressures of 1, 8 and 12 bars on a hollow-cone, simplex pressure-swirl atomizer operating at a liquid flow rate of 75 g/s and a pressure drop of 49 bars, the following conclusions are drawn :

1. All the experimental data obtained on the influence of ambient air pressure on mean drop-size show that a continuous increase in P_A above the normal atmospheric value is accompanied by a continuous increase in overall SMD.
2. The rate of increase of overall SMD with P_A declines with increase in P_A .
3. For all three levels of pressure, the measured local values of SMD are lowest at the center of the spray and increase with radial distance from the spray axis, reaching a maximum in the outer regions of the spray.
4. Increases in P_A tend to make the spray more homogeneous in terms of mean drop size and drop-size distribution. As pressure levels rise from 1 to 12 bars, the radial variation in SMD diminishes and the spray becomes more monodisperse, with values of the Rosin-Rammler distribution parameter q increasing from 3.0 to 3.9.
5. The observed effects of variations in P_A on spray SMD can be explained in terms of the influence of P_A on the spray cone angle and the Weber number of the disintegrating liquid sheet.
6. At high levels of P_A the mean axial velocities of the droplets in the spray decline rapidly with increase in radial distance from the spray axis due to the high aerodynamic drag forces exerted on the droplets in the outer regions of the spray.
7. With increase in air pressure above 1 bar, the normal "hollow-cone" spray gradually moves toward a "solid cone" configuration in which the radial maldistribution of volume flux is much less pronounced.
8. Number density increases with increases in air pressure and radial distance from the spray axis.

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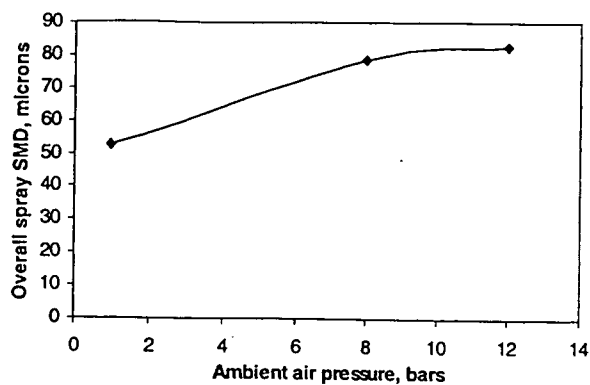


Fig 1. Influence of ambient air pressure on overall spray SMD.

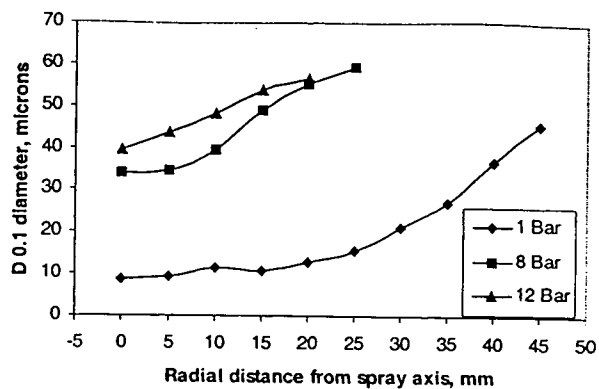


Fig 3. Influence of ambient air pressure on $D_{0.1}$.

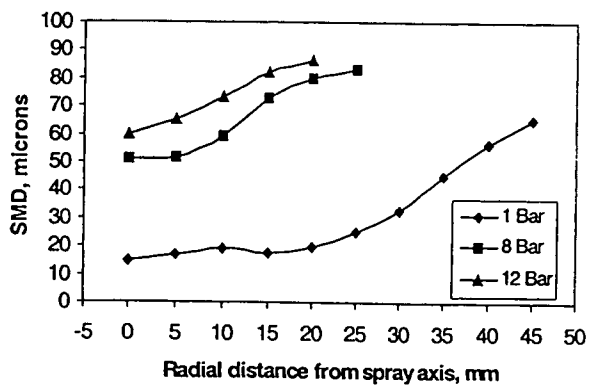


Fig 2. Influence of ambient air pressure on SMD.

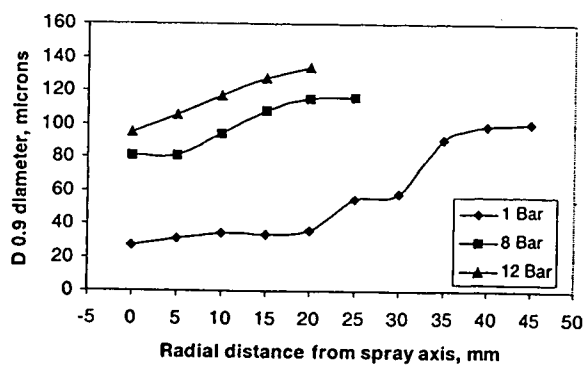


Fig 4. Influence of ambient air pressure on $D_{0.9}$.

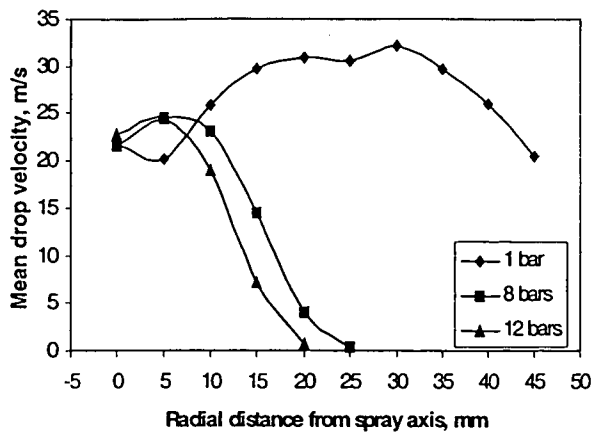


Fig 5. Influence of ambient air pressure on drop mean velocity.

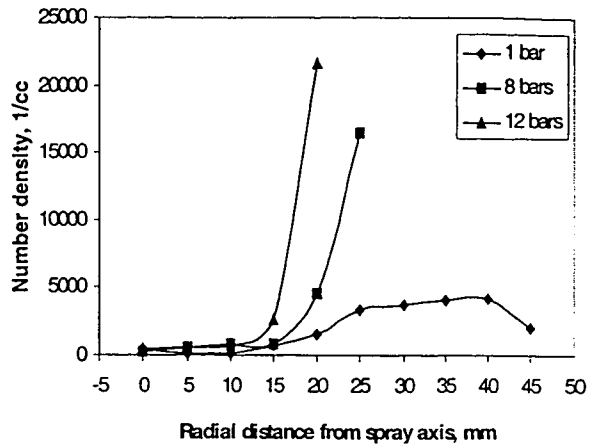


Fig 7. Influence of ambient air pressure on number density.

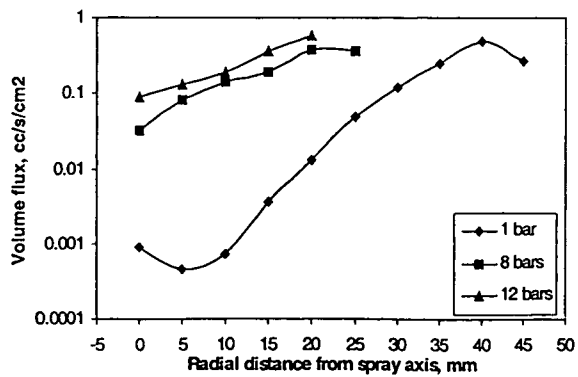


Fig 6. Influence of ambient air pressure on volume flux.