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**Characterisation of mixture preparation
in lean premixed prevaporised combustor modules
by planar laser fluorescence imaging
and computational fluid dynamics modelling**

Supervisor: Prof. D. A. Greenhalgh

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**This thesis is submitted in partial fulfilment of the requirements for the
Degree of Doctor of Philosophy**

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Abstract

In order to minimise the environmental impact of combustion emissions, radically new combustor concepts are under development. Lean premixed prevaporised (LPP) combustion has the greatest potential to achieve low emissions, particularly with respect to oxides of nitrogen. The role of fuel preparation is crucial in the success of the LPP combustor concept.

Planar laser-induced fluorescence (PLIF) has been used to determine fuel placement and concentration, while computational fluid dynamics (CFD) has provided insight into the internal aerodynamics of two premixers. In order to determine the local equivalence ratios in a realistic device a calibration method, for the PLIF signal, has been derived. The vapour phase fluorescence of naphthalene, in the presence of oxygen, was calibrated against known conditions of temperatures and air-fuel ratios. This calibration was undertaken for an atmospheric and isothermal (non-combusting) flow.

With regard to the small engine LPP module, PLIF measurements of the vapour fuel provided images of quantitative local equivalence ratios, at the exit of the premixer. In addition, based on the results of the liquid-phase measurements the evaporated fuel fraction was estimated. The computed droplet trajectories, within the premixing duct, highlighted the importance of the initial fuel dispersion from the injector. Two approaches were identified for improving the vaporisation and increasing the homogeneity of the air-fuel mixture.

The large engine LPP module was investigated for several geometries and operating conditions. The evolution of the fuel dispersion, for those geometries, was characterised by PLIF images of the vapour fuel. In addition, the flame position inside the optical premixing duct was captured by video imaging for each geometry. 2D and 3D CFD simulations were performed to provide an insight into the aerodynamics of the premixer. These results were the basis of a schematic fuel jet breakup study, for two different injector configurations. Finally, the operational characteristics of this novel LPP module, featuring a conical centre-body, are discussed.

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Abbreviations

2D	Two dimensional
3D	Three dimensional
AFR	Air-fuel ratio
CAD	Computer aided design
CARS	Coherent anti-Stokes spectrometry
CCD	Charged coupled device
CFD	Computational fluid dynamics
DGV	Doppler global velocimetry
DNS	Direct numerical simulation
fps	frames per second
IC	Internal combustion
ICCD	Intensified charged coupled device
LBO	Lean blow out
LDA	Laser Doppler anemometry
LDI	Lean direct injection
LDV	Laser Doppler velocimetry
LIF	Laser induced fluorescence
LII	Laser induced incandescence
LPP	Lean premixed prevaporised
MCP	Micro-channel plate
NO _x	Oxides of Nitrogen
PDA	Phase Doppler anemometry
PG	Pulse generator
PLIF	Planar laser induced fluorescence
RQL	Rich-quench-lean
RR	Rolls-Royce Ltd.
SMD	Sauter mean diameter
TM	Turboméca Ltd.
UV	Ultra-violet
XeCl	Xenon chloride

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Chapter 1

Introduction

The drive behind the recent developments in the design of new generation combustors has been primarily motivated by environmental considerations. Growing environmental awareness and knowledge of combustion related phenomenon such as the green house effect, photochemical smog, acid rain and stratospheric ozone depletion have given birth to stringent emission regulations, particularly with respect to nitrogen oxide (NO_x) emissions. Consequently, there has been a substantial world-wide research effort investigating technological solutions aimed at creating “cleaner” combustors. The present study is part of the European *Brite-EuRam Low NO_x* programme which is devoted to the evaluation of the most promising NO_x reduction techniques. Among those techniques lean premixed prevaporised (LPP) combustor concept offers the best prospect and potential for ultra low levels of NO_x. The present project constitutes an investigation and characterisation of the LPP combustor modules.

In a conventional gas turbine combustor, the fuel and air are introduced separately in the primary zone of combustion. The combustion is stabilised in the primary zone under intense recirculation and stoichiometric air-fuel ratio (AFR). Stoichiometric combustion is associated with high flame temperatures and NO_x emissions which increase exponentially with temperature. As a result, the combustion temperature is the primary parameter governing NO_x emissions. In addition, lean mixtures result in lower flame temperatures than stoichiometric mixtures. Therefore, fuel lean operation is attractive in reducing the flame temperature and subsequently the NO_x emissions. Moreover, in order to ensure homogeneous reaction temperatures, careful premixing of the air and the fuel becomes important and necessary. In practice, perfect premixing is difficult to achieve and the word premixed often refers to the aim of the process rather than its realisation (Fric, 1993). Since the aero-engine gas turbines operate with liquid fuel, atomisation and vaporisation of the fuel, prior to combustion, is an additional requirement compared with industrial applications employing gaseous fuels. The

vaporisation is intended to avoid localised fuel rich pockets with stoichiometric combustion. ***Lean, premixed, prevaporised*** combustion thus constitutes the most radical departure from the conventional gas turbine combustor concept.

Lean operation and premixing, however, result in a decrease in stability and operability. Below a certain lean limit the combustor can suffer from lean blow out, which is a major safety issue in flight. At high pressures and temperatures, the fuel can potentially autoignite after only a few milliseconds. This leaves a relatively short time for the fuel to be vaporised and uniformly mixed with the air flow. Furthermore, the mixture velocity must be higher or equal to that of the turbulent flame speed, at all operating conditions, in order to avoid flame flashback and to allow flame front stabilisation. "As a result of the trade-off between the stability and the emissions, optimum performance will be attained not with ideal mixing but rather with an intelligent strategy of fuel placement and mixing" (McDonell & Samuelsen, 2000).

From the above discussion, it becomes apparent that the characterisation of the local air-fuel-ratio is of great importance and interest in assessing the mixing and performance of a LPP combustor module. At present, LPP combustors have not been applied to an operating aero-engine due to high pressure ratios and temperatures promoting autoignition and flame flashback. Nevertheless, this concept is under development and its operational features must be understood prior to a successful application to an aero-engine.

Therefore, the ambition of the present investigation is to develop a better understanding of the LPP modules by characterising the mixture preparation and the air-fuel mixing prior to combustion. To this end, two LPP modules, developed during the early stages of the Brite-EuRam project, were the object of this characterisation. The first one was designed by Turboméca Ltd. (France) for a small gas turbine engine, of the kind typically used for helicopter propulsion. The second was schematically designed by Rolls-Royce plc. (Derby) for large engines, say typically a civil transport aircraft. Although, originally intended for aero-engines both LPP modules can potentially be employed in industrial applications. Planar laser induced fluorescence (PLIF) was used as a diagnostic technique for the fuel concentration measurements. It allows non-intrusive and 2D measurement of the fuel-air distribution with high temporal

and spatial resolution. Computational fluid dynamics (CFD) modelling has also been used for the above objectives in order to provide further information on the characteristics of the LPP premixing modules. The combination of experimental and modelling approaches thus not only provides a complementary picture of the LPP module characteristics but also serves as a CFD validation exercise.

This thesis is divided into three main parts: a calibration section for the study of the vapour and liquid phase fluorescence signal, an experimental and CFD investigation of the small engine LPP module and finally the characterisation of the large engine LPP module both experimentally and by CFD modelling.

The thesis begins with a review of the main gas turbine emissions and their impact on the environment. This is then followed by the introduction of the available low NO_x emission technologies. The potential of the LPP combustor concept as the most promising ultra low NO_x technology is then identified. The operational issues, although not exclusively associated with the LPP combustor concept, are finally discussed. Chapter 3 provides a review of the diagnostics applied primarily to gas turbine combustors. The advantages and the limitations of each technique are discussed. Among those techniques, planar LIF has been identified as the most effective method in the study of the mixture preparation and fuel placement investigations. As a result, PLIF constitutes the diagnostic method of choice for the present study. The fundamentals of LIF are then reviewed at the beginning of Chapter 4. A summary of the AFR measurements by PLIF is presented and a strategy for quantitative fluorescence signal calibration of the vapour phase is described. A preliminary investigation of the liquid phase fluorescence calibration has also been undertaken.

Chapter 5 presents the results of the first application of the above calibration procedure in the characterisation of the small engine LPP duct. Quantitative vapour phase equivalence ratio images, at the exit of the duct, are obtained and qualitative information on the liquid phase is also gained. In addition, some CFD results are also included for comparison between the experiments and the simulations. In light of the experimental and the modelling results a proposal for improving the vaporisation and premixing performance of this LPP module is made.

Chapter 6 is devoted to the experimental study of the large engine LPP module. Qualitative fluorescence measurements of the fuel vapour placement for various geometries and operating conditions are presented. Video evidence of the flame position and structure in the LPP premixing duct was also gathered. In order to gain insight into the aerodynamics of the duct, 2D and 3D simulations of the large engine LPP duct were carried out and are presented in Chapter 7. As a result of these simulations, a schematic and preliminary investigation of the fuel jet penetration is carried out and a summary of the main characteristics of this premixing module is provided. Finally, Chapter 8 is a review of the achievements of the present work. The main findings of the project with respect to both LPP modules are detailed. Recommendations for possible improvements, based on the observations and measurements of this investigation, are included.

Chapter 2

Motivation for Lean Premixed Prevaporised (LPP) combustion

2.1 Introduction

There has been growing concerns over the environmental effect of the exhaust emissions of combustion devices, such as internal combustion engines, gas turbines and other industrial processes. This, in turn, has led to stringent emission regulations and consequently research aimed at creating “cleaner” combustors. This chapter is intended to examine the interest in low emission combustion technology for gas turbines and the operational challenges that it faces. To this end, first the basics of gas turbine emissions with their impact on the environment are briefly discussed. This is followed by a review of low emission combustor concepts, with the emphasis, though not exclusively, on aero-engines. A comparison of those advanced techniques showed the potential of LPP combustion as an ultra low emission technology. Finally, some of the issues associated with the operation of the LPP combustors are discussed.

2.2 Emission legislation and research

The vast majority of the commercial jet aircraft fleet cruises essentially in the upper troposphere and lower stratosphere (about 9-12 km altitude). Moreover, since the early 1970s, there has been a small fleet of 13 supersonic Concorde aircraft in operation cruising at altitudes of 16.5 km. The role of nitrogen oxides (NO_x) from supersonic aircraft fleet on the destruction of the stratospheric ozone has been recognised since the early 1970s (Brasseur *et al.*, 1998). The Clean Air Act (CAA) of 1990 in the United States has resulted in efforts examining the atmospheric effects of the future fleet of supersonic aircraft (Dunston & Human, 1995). In Europe, given the predicted growth of civil subsonic air traffic, efforts have been focused on the effects of subsonic aircraft since 1992 (Amanatidis & Angeletti, 1998). European sponsored projects such as AERONOX and POLINAT have respectively studied the impact of NO_x emissions from

aircraft upon the atmosphere at flight altitudes of 8-15 km and aircraft pollutant emissions in the north Atlantic flight corridor. Among other projects, LOW NO_x has been devoted to the evaluation of most promising NO_x reduction techniques. Therefore, research has aimed at gathering up to date knowledge on the atmospheric effects of aviation and the potential technological solutions, so that realistic emission certification procedures with regulatory bodies such as the international civil aviation organisation (ICAO) can be defined (Schumann, 1996).

2.3 Gas turbine emissions

The exhaust emission of an aircraft gas turbine is primarily composed of soot (smoke), unburned hydrocarbons (UHC), carbon dioxide (CO₂), water vapour (H₂O), carbon monoxide (CO), oxides of sulphur (SO_x) and oxides of nitrogen (NO_x) (Snape & Metcalf, 1990). Soot emission, as smoke, usually is produced at high power conditions, particularly during take off. In these conditions, the engine operates at maximum pressure and temperature. Since the combustion takes place in a fuel rich environment soot is formed as consequence of deficiency in oxygen. On the other hand, UHC are produced at low power, with the maximum at idle, due to incomplete combustion. Carbon dioxide and water vapour, although not always considered as pollutants, are necessary products of complete combustion of a hydrocarbon fuel. A more detailed description of the formation mechanisms of CO, SO_x and NO_x is given next.

2.3.1 Formation and oxidation of CO

Partial and incomplete oxidation of the fuel produces carbon monoxide. In the high temperature flame zone, the reaction rates of the oxidation of fuel molecules by radicals such as hydroxyl (OH) are much higher than that of CO and can reach concentrations of 100-1000 ppm (parts per million).



In the dilution zone of the combustor where temperatures are lower, CO can be oxidised into CO₂. However, oxidation is twice as fast at 1800 K than at 1150 K and is strongly coupled with post-flame turbulence (Correa, 1992).

2.3.2 Oxides of sulphur (SO_x)

Sulphur is contained in the fuel and upon oxidation is converted to SO₂ and SO₃. In aircraft gas turbines sulphur is not a major concern, since fuel specifications allow 0.3% sulphur content (Snape, 1990). However, the exhaust carbon particles are believed to interact with SO₃ resulting in the formation of condensation nuclei. These nuclei may lead to the formation of contrails and cirrus cloud which affect ground temperatures by radiative forcing (Black, 1999). Moreover, in industrial gas turbines that use residual fuel, it constitutes a pollutant of concern as it leads to the formation of sulphuric acid in the atmosphere. The only viable solution in minimising the impact of SO_x is the removal of sulphur from the fuel.

2.3.3 Oxides of nitrogen (NO_x)

Oxides of nitrogen encompass nitrous oxide (N₂O) and NO_x. The latter involves the combined concentration of nitric oxide (NO) and nitrogen dioxide (NO₂) (Roy, 1998). The post combustion concentration of the NO_x, however, is in excess of 90% NO. Since NO can be oxidised to NO₂, it is common practice to combine the concentration of these two species and present the result in terms of NO_x. There are four different mechanisms of NO formation, namely thermal NO, nitrous oxide mechanism, prompt NO and fuel NO. A review of these mechanisms is presented by Lefebvre (1995) and is described briefly in the following section.

- **Thermal NO**

Thermal NO is produced by the oxidation of the atmospheric nitrogen and peaks at the fuel lean side of stoichiometric where the temperatures are high. The reactions are described by the extended Zeldovich mechanism.



The production of thermal NO is significant at temperatures of above 1850 K and is very sensitive to flame temperature since reactions (2.2) and (2.3) are endothermic.

- **Nitrous oxide (N₂O) mechanism**

At high temperatures this mechanism is initiated by the oxidation of nitrogen in the flame front (reaction 2.5). At lower flame temperatures (less than 1350 K) nitrous oxide is formed through the reaction described by equation 2.6 (Lewise & Greenhalgh, 1993).



N₂O can be further oxidised into NO by reacting with oxygen, hydrogen and carbon monoxide as described by the following reactions.



- **Prompt NO**

The observation of a non zero profile of NO just upstream of a flat hydrocarbon flame front revealed the presence of NO very early in the combustion process (Fenimore, 1971). Although, prompt NO mechanism is complex it is believed that it is initiated by the CH radical.



In lean-premixed conditions, the HCN oxidises mainly to NO through reactions involving HCN, CN and NCO.

- **Fuel NO**

If the composition of the fuel contains nitrogen, some of it eventually will form the so called fuel NO. The content of light to heavy distillate fuel can vary in typically between 0.06 to 1.8%. The rate of conversion is very slightly dependent on temperature. Aviation fuel contains very little fuel bound nitrogen and fuel NO is of minor concern in terms of emissions. A study, conducted by Capehart *et al.* (1997), showed that in an atmospheric pressure jet-stirred reactor (fitted with a prevaporising-premixing chamber) the organic nitrogen conversion into NO was between 70 to 100% with a fuel containing 0.0124% nitrogen by mass.

In a lean premixed combustor burning methane at 1900 K and an equivalence ratio of around 0.8, the contribution of thermal, nitrous oxide and prompt were respectively 60, 10 and 30 percent. At lower temperatures and equivalence ratios this proportion can change dramatically. It was observed that for the same combustor operating at 1500 K and an equivalence ratio of 0.6, the contributions were 5% thermal, 30% nitrous oxide and 65% prompt NO. At low temperatures (below 1800 K) the prompt mechanism is dominant whereas at higher temperatures the thermal NO is the main mechanism of NO_x formation. The exponential temperature dependence of NO_x emissions was shown in an industrial gas turbine burning natural gas, where a 400 K reduction of the flame temperature resulted in half the overall NO_x emissions (Lefebvre, 1995).

2.4 Environmental impact of gas turbine emissions

Despite the fact that the current fleet of Concorde aircraft, at this moment in time, is undergoing modifications for airworthiness, the prospects for a second generation supersonic transport is judged favourable. The subsonic and supersonic passenger traffic is anticipated to triple between 1990 and 2010 and to further double from 2010 to 2030 (Swadling, 1993). This new supersonic transport is expected to reach operational status by 2010 (Saounatsos, 1998).

Although the current aviation fuel consumption is about 3% of the fossil fuels used worldwide, its impact on the environment must be considered with special attention. The injection of pollutant emissions into the upper atmosphere has the potential to affect it more directly than any other source of combustion. Industrial gas turbines, mainly used in power generation, can also contribute adversely to the air quality on an urban level. A brief review of the main atmospheric effects of gas turbine emissions is provided next.

The greenhouse effect

The Earth's surface emits infra-red radiation which is absorbed by CO₂. This radiation is directed back towards the surface of the Earth resulting in an increased temperature. This is known as the greenhouse effect. The contribution of the current worldwide aircraft fleet is very small and their impact is thought to be limited. However, with the

growth of the air traffic and the associated increase in fuel consumption, this effect may become more important.

Effect of contrails

Although water vapour, released by aircraft engines, is not a pollutant its impact on the atmosphere can be more significant than that of CO₂. On average, contrails (satellite data), cover about 0.4% of the sky over central Europe and about 1% over the North Atlantic ocean. When compared with natural cirrus clouds, covering 20% of the sky, their radiative effect may be significant. In addition, it is thought that water could also increase the frequency of occurrence of polar clouds, where effectively ozone is depleted.

Ozone production and depletion

NO_x emissions, released in the troposphere and lower stratosphere (9-12 km altitude), where subsonic aircraft operate lead to the production of ozone harmful to human health at high concentrations.

At higher altitudes, in the stratosphere (16-25 km), NO_x can contribute to the depletion of the ozone layer. For fuel economy reasons supersonic aircraft operate at these altitudes where the natural concentration of the ozone is the highest (Figure 2.1). Stratospheric ozone depletion results in an increased ground level ultraviolet radiation with consequences on higher incidence of skin cancer.

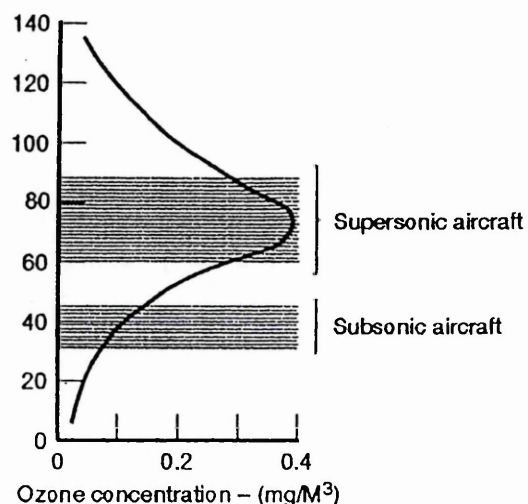


Figure 2.1 Ozone concentration variation with altitude (x1000 foot)
(Koff, 1994)

Smog and acid rain

In the presence of sunlight, at ground level, carbon monoxide, nitrogen oxides and unburned hydrocarbons lead to photochemical smog with eye and respiratory irritation as main effects. In addition, NO_x released at ground level is dispersed in the troposphere due to intense weather process. They react with OH radicals to produce HNO₃ (nitric acid) which is dissipated in the form of acid rain.

The increased knowledge of the environmental impact of emissions, combined with public concerns, have resulted in legislation and regulations. As a response, gas turbine engine manufacturers have undertaken research programs aimed at minimising the impact of those emissions. The potential technological approaches, to this end, are discussed next.

2.5 Advanced low emission combustor concepts

In a conventional gas turbine combustor, the combustion takes place in the primary zone where the flame is stabilised by swirl in a region of vortex flow. The combustion, which is close to stoichiometric, proceeds to near completion due to intense turbulence and sufficient residence time in this region. The hot products of combustion then flow in an intermediate zone where the combustion can complete. The secondary dilution zone provides the turbine with an acceptable mean temperature and temperature distribution. Figure 2.2 shows the schematic representation of a conventional gas turbine combustor.

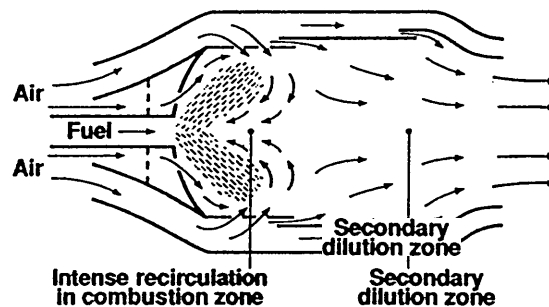


Figure 2.2 Schematic of a conventional gas turbine combustor
(Griffiths & Barnard, 1995)

The combustion in the primary zone occurs under fuel rich conditions and at high temperatures which encourage the production of NO_x. Improvements in combustor design (better atomisation, cooling) and reduced specific fuel consumption have resulted in reduced emissions of CO and UHC. The current combustion efficiencies of gas turbines, at idle and take off, are well above 99.5%. Further reduction of emissions, in particular regarding NO_x, requires new combustion technologies (Koff, 1994).

It is now established that the main parameter governing pollutant emissions, in particular NO_x emissions, is temperature. Therefore, careful control of the latter in the combustion zone offers the best approach in controlling emissions. The well stirred reactor (WSR) represents a laboratory idealisation of an efficient, highly stable and low emission advanced combustion system of the future (Blust *et al.*, 1997). Zelina & Ballal (1994) studied the combustion efficiency and the pollutant emissions of various hydrocarbon fuels in a WSR. They concluded that the minimum CO emissions were obtained at equivalence ratios of about 0.6 and that NO_x peaked near stoichiometric with increased residence time. NO_x emissions were dramatically reduced at lower equivalence ratios.

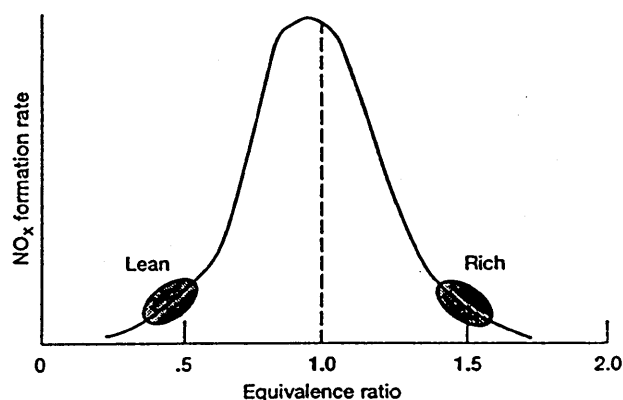


Figure 2.3 NO_x formation as function of equivalence ratio
(Lee *et al.*, 1995)

Figure 2.3 is a schematic representation of NO_x formation as a function of equivalence ratio and shows the incentive of operating fuel lean for reduced NO_x emissions.

2.5.1 Lean direct injection (LDI) combustion

The operating principle of LDI combustion is based on the direct injection of the fuel into the combustion zone. Since large droplets burn stoichiometrically, creating hot spots, it is essential to produce exceptionally small droplets. The injection of these droplets in the combustion zone must be achieved in such a way as to provide complete vaporisation and mixing prior to combustion. Figure 2.4 shows a schematic of the LDI combustor.

Hayashi (1995) studied the emission characteristics of a LDI combustion system, using liquid fuel. The experiment, carried out at atmospheric pressure, at temperatures of 450, 550 and 650 K and equivalence ratios of near flammability limit to 1.2 showed that LDI has the potential of low NO_x emissions and high combustion efficiency (reduced CO and UHC emissions).

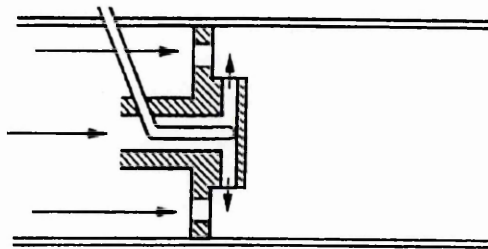


Figure 2.4 Schematic of LDI combustor
(Lyons & Neidzwiecki, 1993)

In a different study, Colantonio (1998) studied the NO_x emissions of a LDI combustor incorporating jet-shear-layer mixing. This scheme involves impinging of radial fuel-air jets with the axial air jets. In addition, an effervescent atomiser was employed using a minute amount of the entry air. Air was injected directly into the fuel upstream of the fuel discharge orifice. A premixing region around the injector was also added for improved fuel-air uniformity and further vaporisation prior to injection in the primary combustion zone. Although relatively high NO_x emissions were observed, it was concluded that further developments in jet-shear-layer mixing and atomiser design could allow lower NO_x and higher combustion efficiency.

2.5.2 Rich-quench-lean burn (RQL) combustion

Another candidate for low NO_x emissions is the rich-burn, quick-quench, lean-burn (RQL) combustor. This concept uses staged burning in order to achieve low emissions. It was originally designed as a solution to overcome NO_x emissions from fuels containing nitrogen, in industrial gas turbines. The combustion is initiated in a fuel rich zone where the lack of oxygen and the lowered combustion temperatures limit NO_x emissions. Fuel bound nitrogen, under those conditions, is converted to non-reactive N₂ (Feitelberg & Lacey, 1998). This stage is followed by a quenching zone where air is added to the combustion products of the rich zone, reducing their temperature to levels where NO_x production is minimal. This transition from rich to lean combustion must take place rapidly if stoichiometric NO_x emissions are to be avoided. The combustion then proceeds to completion in the final stage, namely the lean-burn zone (see Figure 2.5). Beyond the importance of the mixture quality in the fuel rich zone, unarguably the success of RQL lies in the ability of achieving instantaneous mixing in the quick-quench zone.

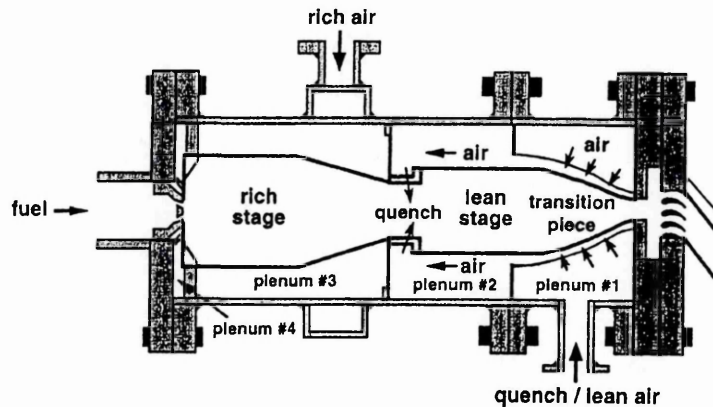


Figure 2.5 A schematic of the RQL combustor
(Feitelberg & Lacey, 1998)

Blomeyer *et al.* (1999) investigated the optimisation of the quick-quench zone for a RQL combustor. The mixing zone consisted of three parallel ducts of constant rectangular cross sections. The two main experimental configurations were in-line jet axis (opposed row of jets) and the staggered configuration, where the opposed jets were off-set relative to each other, to avoid their impingement. They suggested correlation for optimal jet to crossflow momentum-flux ratio, as a function of height,

diameter and spacing of the quenching holes. It was also noticed that the mainstream swirl was an important parameter that must be taken into account in the design of the quench zone. In a realistic combustor, however, over the operating range of the engine, the optimum mixing may ultimately require variable geometry (Tacina, 1990).

2.5.3 Catalytic combustion

In industrial gas turbines, for power generation, the most effective techniques of controlling NO_x are wet diluent injection (WDI) or lean premixed dry low NO_x combustion (DLN). However, for ultra low NO_x emissions of less than 5 ppm, they must be combined with selective catalytic reduction (SCR) which consists of a denitrification of the exhaust gases (Betta *et al.*, 1996). Wet diluent injection consists of injecting water or steam into the combustion zone to lower the temperature. The operating cost of this approach is high mainly due to the requirement of high water purity. DLN uses an optimised combustor design to provide control over the mixing and the fuel-air-ratio distribution, for controlling the combustion temperature and is often associated with high capital cost. The high consumption of ammonia (almost one mole of ammonia per mole of NO_x) in the SCR systems is also an important economical consideration. Besides, unreacted ammonia can cause catalyst deactivation (Vatcha, 1997).

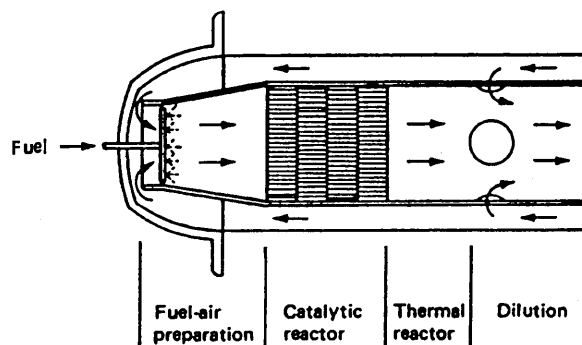


Figure 2.6 Schematic diagram of catalytic combustion (Lefebvre, 1998)

In catalytic combustion (Figure 2.6), the fuel-air mixture reacts at the surface of the catalyst. The oxidation takes place at even lower temperatures (about 1000 °C) than the lean flammability limits. One limitation of the catalyst combustion is that it suffers

from upstream burning (at the entry) or autoignition. Anderson & Tacina (1982) found that steam injection prevented this problem but at the expense of stable combustion. In a further approach, a thermal reaction zone may be added to allow the reactions to complete downstream of the catalyst. In an attempt to overcome the thermal shock fracture of supporting substrate of the catalyst, Ozawa *et al.* (1995) used a postcatalyst premix combustor. In this approach, the temperature of the catalyst was kept very low and additional fuel, injected into the premixing section, increased the combustor outlet temperature to 1570 K.

Siminski & Shaw (1967) studied the use of a catalytic combustor for aircraft gas turbine engines. Although the study was limited to conditions simulating engine idle, they concluded that the durability and the in-flight transient response of the catalyst were major problems. The fracture of the catalyst could damage the turbine with serious safety implications. Even if, catalytic combustion has been applied to industrial applications, it is unlikely that it would be applied to aircraft gas turbines (Metcalf *et al.*, 1991) mainly due to excessive weight and reliability problems.

2.5.4 Lean premixed prevaporised (LPP) combustion

Compared with a conventional gas turbine combustor, where fuel is injected directly into the combustion zone, with very little mixing and vaporisation, LPP combustion constitutes the most radical departure from this concept. Its underlying principle is to provide the combustion zone with a lean and homogeneous mixture of fuel and air. In doing so, the droplet combustion is eliminated and the flame temperature is kept low and uniform, resulting in very little NO_x. In a typical LPP combustor, fuel is injected and is then vaporised and mixed with the air in a premixing-prevaporising duct prior to combustion as shown in Figure 2.7.

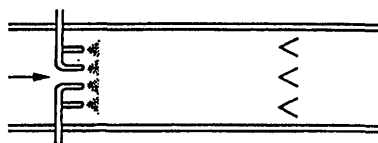


Figure 2.7 Schematic representation of LPP combustion
(Lyons & Neidzwiecki, 1993)

The NO_x reduction potential of a LPP combustor is the highest among low NO_x technologies applicable to aircraft engines. For instance compared with the RQL combustor concept, LPP provides lower NO_x levels (Gupta, 1993). In a comparative study of LDI, RQL and LPP concepts, Tacina (1990) observed lower NO_x values for LPP than for RQL combustor. He suggested that the quick-quench zone of the RQL combustor may be an important contributor to the total NO_x emissions. When comparing LPP and LDI, they showed similar NO_x levels but for gaseous fuels. However, the use of liquid fuels increased NO_x emissions in both cases, since partial vaporisation of the fuel created a higher level of unmixedness (Hoffmann *et al.*, 1998).

2.6 Associated issues in LPP combustion

Although LPP combustion concept has the lowest NO_x emission potential, there are a few problems associated with its operation. These are to a certain extent, applicable to any combustors, particularly low emission combustors, and must be considered at the design stage. The following section provides a brief description of those issues.

2.6.1 Autoignition

Autoignition is a process where in the absence of a flame or a spark, the combustible mixture undergoes chemical reaction. Spadaccini & Tevelde (1982) proposed an ignition delay time correlation for aircraft-type fuels. The influence of pressure, temperature and the equivalence ratio is important on the ignition delay time and is dependant upon hardware configuration and particularly the fuel injector design (Tacina, 1983). In design of combustors, the residence time is kept well below this ignition delay to avoid autoignition.

2.6.2 Flashback

Flashback is an intrinsic feature of all premixed-fuel combustion systems. Flashback is the upstream propagation of the flame from the combustion zone into the premixing duct (Proctor & T'ien, 1985). In other words, if the turbulent burning velocity of the

flame is higher than that of the incoming fuel-air mixture flow, then flashback occurs. This can happen either in the free stream or along the boundary layer (low velocity regions) of the premixing duct walls. A flashback arrestor design for LPP combustors was proposed by Kraemer & Lee (1998). However, the best strategy to avoid flashback is to ensure that the velocity of the main flow always remains higher than that of the flame front.

2.6.3 Lean blow out (LBO)

In an aero-engine and industrial gas turbine the flame stability and sustained combustion are of paramount importance to safety and combustor performance. For aircraft engine, combustor blow out is encountered at high altitudes and low engine speeds. In industrial application, to achieve ultralow NO_x emissions, the combustor is required to operate near the lean blow out limit (Durbin *et al.*, 1996). The stabilisation of the flame often requires use of swirler (Gupta *et al.*, 1998) or a bluff body to which the flame is anchored. Driscoll & Chen (1986) studied the stability limits of a swirl-stabilised flame and noticed three limits where lean blow out occurred. Lean blow out was a result of either an excessive fuel velocity, an excessive swirl or insufficient swirl. In an investigation of LBO limits of an optical generic gas turbine combustor Switzer *et al.* (1994) concluded that even in simple cases the flow is far too complex to allow generalised modelling of the LBO, applicable to a realistic combustor.

2.6.4 Acoustics

Another problem of all lean combustion systems is acoustic resonance, which in severe cases can lead to vibrations and mechanical integrity problems. In conventional combustors, the liner (combustor wall) acts as a sound attenuator. Thermoacoustic instabilities, which generate resonant sound, are almost entirely suppressed by liner cooling holes and mixing nozzles. In a study of thermoacoustic oscillations, Keller (1995) concluded that the leading cause of combustion driven oscillations in modern Low NO_x combustors is a result of the fluctuations in the rate of reaction. These fluctuations can be coupled with periodic lean extinction and vortex roll up in the primary zone of combustion. In other words, the heat release perturbations excite the

pressure fluctuations which, in turn, enhance the heat release fluctuations (Richards *et al.*, 1999).

Two strategies are adopted in the control of combustion instabilities, namely passive and active control. In the passive control approach, modifications such as, geometry alteration and gradual diameter changes are undertaken. On the other hand, active control, in real time, has been demonstrated by the use of loudspeakers 180 degrees out of phase with the established oscillations. However, pressure field oscillation control is not very practical in realistic devices, particularly when large heat release rates are involved. An alternative to this approach is fuel flow modulation. It can be applied either to the entire fuel flow or to part of it (secondary fuel injection). In this latter control strategy, the secondary fuel can be injected at much lower frequencies relative to that of the flame oscillation (Jones *et al.*, 1999).

2.7 Summary

The growing awareness of the direct impact of the combustion emissions on the environment, from gas turbine combustors, has given birth to stringent emission legislation. In response to those regulations, gas turbine engine manufacturers have investigated several potential combustion concepts capable of low emissions, in particular with respect to NO_x. Lean premixed prevaporised (LPP) combustion, is the most radically innovative of those concepts and has the strongest potential of achieving ultralow levels of NO_x. Despite operational issues associated with it, though not exclusive to LPP combustion, it is actively under development. The present study is a contribution in the characterisation and understanding of this promising concept.

Chapter 3

Diagnostics in gas turbine combustors

3.1 Introduction

Until recently the combustion engineer has had limited access to advanced diagnostic techniques. The prevailing design approach has been the use of empirical relations and partly “trial and error”. With the requirement of low emission combustors to satisfy stringent environmental regulations, better understanding of the mechanisms involved in mixture and pollutant formations have to be gained. At the same time, the advent of reliable and powerful lasers has resulted in the development of non-intrusive laser based techniques which have been applied to a variety of practical problems. This chapter is a review of the various tools which have been used to gain insight into such mechanisms. A brief description of each technique, with their advantages and limitations, is provided.

3.2 Gas sampling

Gas sampling probes have been extensively used in the study of emissions, the mean mixing characteristics and mean fuel-air-ratios in gas turbine combustors. Since this approach is intrusive the presence of the probe disturbs the flow field near the sampling region and affects the accuracy of the measurements, particularly in turbulent flows. Besides, physical probes suffer from a limited spatial resolution and temporal response. The gas analysers are often remote from the combustor and the sample transport time can be in the order of a few seconds. Consequently, the results are time averaged and have no temporal resolution. At high temperatures and pressures, the probes are often water cooled. The purpose of water cooling is two fold. It allows the probe to survive at those conditions and also minimises the progress of the chemical reactions within the gas sampling tube. This quenching of the hot gases is intended to preserve the nature of the sample from the point of collection to where it is analysed

(Hurley *et al.*, 1999). By using a probe, Hurley (1993) reported on smoke measurements inside a gas turbine combustor. He chose a continuous sampling method based on the measurement of scattered light from the smoke. The probe was calibrated in situ and used in parallel with a filter stain instrument. The calibration consisted of collected gravimetric samples on glass fibre filter papers. However, it was found that due to scatter in the calibration plot and 10% loss of smoke in the sample lines (10 m long), the overall accuracy was about $\pm 30\%$.

Noyce *et al.* (1981) used gas sampling to study the emission and the mixing characteristics of a gas turbine combustor. The degree of mixing was varied by the use of two different fuel injector nozzles. The experiments were carried out at atmospheric pressure for a constant equivalence ratio, burning propane. They concluded that the main factor influencing the mixing in this combustor was the primary air addition in the primary zone of combustion. In an extension of this study Noyce & Sheppard (1982) carried out similar measurements for a range of equivalence ratios. They concluded that the fuel injection method had an important effect in the performance of the primary zone of combustion. They also noticed important changes, within the primary zone, in the degree of mixing for increased fuel flow rates. The generated data, in both these investigations, was also intended for validating and developing computer models.

3.3 Optical fibre techniques

Optical fibre is a medium which allows light to be guided with high transmission efficiency. The optical probe is often connected to a photomultiplier for processing of the results. This method has the advantage of temporal resolution.

In a study of local equivalence ratio variation of nozzles in lean-premixed combustion, Bandaru *et al.* (1998) used this technique. The optical fibre was installed in the centre body of the mixing section of the fuel nozzle to monitor the chemiluminescence of the flame. The chemiluminescence of electronically excited radicals and combustion products in a flame is a result of the chemical reactions (Kojima *et al.*, 2000). The probe was placed behind the flame and connected to a photomultiplier. They monitored

the variation of the intensity of CO_2^* and CH^* as an indication of reaction and heat release rates. They concluded that the probe can be potentially used in gas turbine combustors for determining the equivalence ratio and active control of the combustor.

Lee & Santavicca (1997) used a fibre optic equivalence ratio probe based on laser induced fluorescence. The probe was made of a water cooled stainless steel jacket and contained two fibres, one for transmitting the laser beam and the other for collecting the fluorescence signal. The layout of the optics inside the probe was such that the measurement volume was off set relative to the tip of the probe. This reduced the impact of the probe on the mixing characteristics at the region of interest. Acetone was chosen as fluorescent fuel marker and a concentration of one percent was necessary to measure equivalence ratios of about 0.1 when burning methane. The probe was calibrated at pressures up to 12 atmosphere and temperatures of 400 °C. When applied to a turbulent axisymmetric jet, they concluded that the mean and fluctuations of the equivalence ratio could be determined with an accuracy of 5%.

3.4 Raman & Rayleigh scattering

When a laser beam interacts with molecules along its path, light is scattered as a result. This scattered light can either have the same wavelength as the incident light (elastic scattering) or a different one (inelastic scattering). Both Raman and Rayleigh are based on this principle and have been used in the study of major combustion species.

Raman scattering is the inelastic scattering of light from molecules. Depending on the energy exchange process between the incident light and the molecule it can be termed rotational, vibrational or electronic. If the scattered light has a shorter wavelength relative to the incident light it is called anti-stokes Raman, and stokes Raman when there is an up shift in the wavelength. Raman scattering is species specific and since each molecule has a distinctive frequency shift, multiple species measurements are possible. The Raman signal is proportional to the number density of the species and is very weak. The 2D use of Raman scattering is therefore limited unless the pressures

are quite high. The main interferences, with the Raman signal, are flame luminosity, soot incandescence and scattering from particles. Raman is used for temperature and species mapping. Rayleigh scattering is elastic and is much stronger than Raman scattering. It is not species specific and is a measure of the total gas density. It allows temperature measurements by the use of the density and the perfect gas law. However, since particles, such as dust, also scatter light in an elastic manner (Mie scattering) with a much stronger scattering, Rayleigh is restricted to particulate free applications (Eckbreth, 1996).

In an attempt to gather data for combustion modelling, Nandula *et al.* (1996) reported on detailed measurement of major species in a lean premixed combustor. The measurements were performed in a bluff-body stabilised turbulent combustor burning methane-air at an equivalence ratio of 0.586. The scattered Raman and Rayleigh signals were collected into a photomultiplier which was aligned at the exit of a spectrometer. The molar concentration of species, such as CH₄, O₂, N₂, CO₂ were determined using Raman scattering and were at adiabatic equilibrium at the exit plane of the combustor (six diameters downstream). Based on the temperature measurements, from Rayleigh scattering, they deduced a value of 0.925 for the reaction progress variable (measure of completeness of combustion) in the recirculation zone. Similar measurements, based on Raman scattering, are also reported by Gittins *et al.* (2000) in a model gas turbine combustor burning aviation fuel at high pressures.

3.5 Coherent anti-Stokes Raman spectroscopy (CARS)

CARS has been widely used for temperature and species concentration measurements. It has a strong signal and is suited for the study of harsh environments. However, it is mainly restricted to the measurement of major constituents (typically above 1%). The CARS signal is generated through the interaction of two laser beams (pump and Stokes) at different wavelengths. The laser-like signal which is a function of the frequency of these two beams is a coherent signal. CARS signal generated at a given location would be phased with the CARS signal generated at a different location.

The CARS signal is directed to a spectrometer for analysis of intensity and frequency. This spectral identity of the signal is both mole fraction and temperature dependant and is the basis of their measurement. However, limited in principle to point-wise measurements, CARS is alignment-critical and suffers from large temperature fluctuations (Locke *et al.*, 1998).

Hedman & Warren (1995) applied CARS to detailed temperature mapping of a model combustor using a practical air-blast fuel injector. The measurements were performed using propane and two equivalence ratios (0.75 and 1.50). The isothermal plot of the mean and rms (root-mean-square) for both cases allowed to put in evidence the vortex structure and the recirculation zone. In the fuel lean case the flame was anchored near the injector whereas in the fuel rich case it was observed further downstream. A detailed review of CARS, its fundamenatals and some applications, is available in an article by Greenhalgh (1988).

3.6 Laser-Doppler Anemometry & Phase-Doppler Anemometry

Laser Doppler anemometry (LDA), also termed Laser Doppler velocimetry (LDV), and Phase Doppler anemometry (PDA) are similar techniques in principle. The intersection of two laser beams allows to create a measurement volume in which interference fringes are generated. When particles cross this measurement volume, they scatter intensity modulated light which is collected by a photodetector. LDA indicates the rate of variation of the scattered light which is proportional to the velocity normal to the plane of the fringes. It can simultaneously measure mean and fluctuating velocities, and if three orthogonal fringes are generated, all velocity components can be determined (axial, radial and tangential).

PDA, however, uses the phase shift of the refracted light from a droplet via two or three photodetectors located at different angles relative to the measurement volume. This phase shift is proportional to the diameter of the droplet and, as in LDA, velocity components of the particle are determined at the same time as the diameter. Both LDA and PDA are point wise measurements and detailed planar measurements can often be time consuming.

Burattini *et al.* (1999) used LDA to characterise the velocity field at the exit of a model gas turbine premixer. They used an aerosol fog generator to seed the air flow with vaporised oleos liquid with a mean particle diameter of 2 micrometer. From their measurements at different air flow splitting (swirler, bypass) and equivalence ratios they concluded that, the smallest variations in mean and fluctuating axial velocities corresponded to where the fuel concentration was maximum. They also noticed an influence of the bypass air near the injection holes. They added that, it would be possible to optimise the premixer by changing the number of holes on the injector and altering the bypass ratios.

Harding (1996) used the same approach to determine the velocity distribution and the residence time in the premixing duct of a LPP combustor. The optical duct consisted of a convergent divergent section with straight walls. The velocities were found to be in the range of 100 to 150 m.s⁻¹ in the premixing section. The residence time was estimated to be 0.51 ms in the core of the duct and 0.77 ms at the outer flow, due to the longer path generated by the swirlers.

A correction method for refraction and astigmatism effect of curved optical boundaries have been proposed by Bicen (1982) and Zhang & Eisele (1996) in LDA measurements. Based on this method, Monmont (1999) reported on more accurate results in a similar premixing duct.

PDA has been extensively used for drop sizing measurements, in particular from injectors. Lavergne *et al.* (1992) used PDA to study the liquid sheet atomisation of a simplified airblast injector. The measurement of velocity and drop size was used to assess the effect of the swirl on the overall performance of the atomiser. They found that swirl had a important effect on the velocity, spatial distribution and the number density of the droplets.

Trichet & Bismes (1995), in a comparative study of two fuel injectors in a square section LPP duct, conducted PDA measurements. They compared a pressure swirl and a prefilmer airblast atomiser using methanol. Both cold flow and measurements at about 500 K revealed similar patterns, although with differences. The hollow cone structure of the pressure swirl atomiser was particularly evident. They concluded that,

the initial drop size distribution affects the streamwise droplet distribution. At high temperature conditions volume flux and vaporisation were function of impingement of air on the injectors.

Brandt *et al.* (1996) investigated the liquid fuel evaporation of a flat prefilming airblast atomiser for a LPP combustor. The experiments were carried out at realistic operating conditions with temperatures of up to 850 K and pressures of 15 bars. The evaporation rate was determined by measuring the volume flux of the droplets. At 3 bars, 150 mm downstream of the atomiser, only 70% of the fuel was evaporated compared to 99% at 15 bars. At 550 K (9 bars) , for the same distance, 20% of the fuel was evaporated against 99% at 850 K only 100 mm downstream. At 5 bars and 750 K, the airflow velocity was reduced from 120 m.s⁻¹ to 80 m.s⁻¹. At the last measurement plane (150 mm further down) only 50% of the fuel was evaporated compared with 95% (at higher velocity), despite a increased residence time by a factor of 1.5. They concluded that the initial dropsise distribution influences strongly the evaporation rates. High relative velocity differences between the fuel and air promote this atomisation and subsequently evaporation in such an atomiser.

3.7 Doppler global velocimetry (DGV)

DGV is a planar method for the measurement of velocity. The flow is seeded with particles and the relative frequency shift from the scattered light is determined by a molecular filter that transmits as a function of the frequency of the scattered light. Most often a carefully calibrated iodine-vapour absorption cell is used to this end. The direction of the velocity is determined by the direction of the laser sheet and the direction of the observation. DGV has been applied at high speed flows, typically above 100 m.s⁻¹, and may suffer in recirculating flows where low velocities may cause inaccuracies (McDonell & Samuelsen, 2000).

Roehle *et al.* (2000), used DGV to map the detailed 3D velocity field inside a double staged combustion chamber with two main and three pilot burners. This sector was part of an annular gas turbine combustor of a civil transport aircraft. The measurement

apparatus consisted of a copper vapour laser, three laser sheet generators and an imaging system. This imaging system made use of two CCD (charged coupled device) cameras, one with the reference image and the other combined with the iodine absorption cell. Since the accuracy of the results depended strongly on the vapour pressure and the temperature of the iodine, the cell temperature was kept at about 55-60 °C. The flow was homogeneously seeded with a fog generator using propylene glycol particles (1.5 micrometer diameter). They mapped the velocity field of 50 planes at 2 mm interval with an accuracy of 1.5 m.s⁻¹. Naylor & Kuhlman (1999) applied a two-component DGV in the study of a turbulent pipe flow where they reported an accuracy of 1-2 m.s⁻¹ for velocities in the order of 60m.s⁻¹.

3.8 Laser Induced incandescence (LII)

When soot particles are subject to intense laser fluences, they are heated well above the surrounding gas temperature and as a result radiate strongly enhanced incandescence. Soot particles can rapidly reach temperatures of around 4000 K where the heat loss mechanism is governed by the evaporation of C₂ and C₃ (Tait, 1994). LII is a source of interference in many laser based measurements, such as Rayleigh and Raman scattering, where the experiments are often carried out at lean conditions (soot free) to avoid the influence of the incandescence. LII has been correlated to the number density and the soot volume fraction and is under further development. Calibration of the LII signal for quantitative measurements of soot in applications such as, gas turbine combustors, is under investigation (Grigorian, 2001).

Black (1999) used LII in the study of the exhaust plume of a medium sized military engine. LII was applied as a point wise measurement with back scatter, slightly off axis, collection detector. Although the results were qualitative, a different dependence of the signal was noticed relative to sampling measurements. LII signal increased largely from low to high power conditions, probably due to the fact that at those conditions soot is emitted in the form of agglomerates. With conventional techniques a potential break up of those particles in the probe lines is possible. In addition, large soot particles cool slower than small particles and would yield higher signal levels. It was concluded that

LII signal has a higher rate of change and can be used in monitoring smoke emissions with engine transients, so far unachieved with extractive measurements.

Dec *et al.* (1991) used LII to study the qualitative 2D distribution of soot in an optical direct injection diesel engine. In order to avoid extinction of the laser light, attenuated by soot and droplets, they replaced the diesel fuel with a mixture of hexadecane and ethoxyethyl. This mixture had lower sooting propensity but conserved similar vaporisation properties. They successfully localised the spatial onset of the soot formation. They found that soot was principally present near the centre and the edges of the combusting spray plume. Wainner & Seitzman (1999) in a comparative study, used LII in two different environments. The first consisted of a well-documented diffusion flame and the second of a simulated exhaust flow. They found that there were differences in the LII signal and suggested that it may originate from the differences in the nature of the carbon particles, their age and their internal structure.

3.9 Planar laser induced fluorescence (PLIF)

Laser induced fluorescence (LIF) is the spontaneous emission of light from a given species (atoms or molecules) which has been driven to an excited electronic state by laser excitation. The light is emitted when the excited species return to their electronic ground state. The fluorescence signal intensity is proportional to the initial number density of the species and the fluorescence efficiency. This fluorescence efficiency is primarily a function of the emission rate and the quenching which is composition and temperature dependant and can be difficult to quantify. When a thin light sheet is used, 2D planar imaging of fluorescence can be achieved (PLIF). LIF has high spatial (mm^3) and temporal resolution (10^{-8} to 10^{-6} seconds) (Eckbreth, 1996) and can be applied to species-selective measurements (Georgiev & Aldén, 1997). Given these advantages, LIF has been applied to a variety of measurements and constitutes one of the most widely employed techniques (Hanson, 1997). However, the majority of the applications have focused on the tracking of the flame front, via fluorescence of OH, or have investigated pollutant formation by NO fluorescence.

For instance, Santoro (1998) in a combustion instability study used OH PLIF. A model gas turbine, burning natural gas, was used. He found that the OH fluorescence magnitude varied with the pressure oscillation phase, both in terms of intensity and spatial distribution. The combustion instability was thus characterised by the coupling between pressure oscillations and periodic heat release.

Cooper & Laurendeau (2000) reported quantitative measurements of NO concentration in a LDI spray flame. Point LIF measurements were carried out at different locations within the burner, however due to quenching, the results were qualitative. They used laser saturated fluorescence to account for the quenching factor and scaled the results from the LIF measurements. Other studies of flame structure and combustion species in model gas turbine combustors have also been reported (Hicks *et al.*, 1997 and Foglesong *et al.*, 1999).

Löfström *et al.* (1996) used simultaneous LIF and Mie scattering to study qualitatively the mixing and the vaporisation of the fuel in an industrial gas turbine. The measurements were taken at the exit of the premixing duct for two different operating temperatures (500 to 900 K), equivalence ratios (0.25 to 0.50) and duct configurations. The liquid fuel was standard Jet-A, the spectroscopic properties of which were analysed in detail to allow selection of adequate filtering for each imaging channel (LIF and Mie). Although the results were qualitative, they concluded that the gained information was important for understanding of new concepts of gas turbine combustors such as the LPP concept.

Applications of quantitative measurements of vapour and liquid phase in realistic optical gas turbine combustors and fuel sprays have also been developed by Greenhalgh (2000). PLIF was selected to study the fuel-air mixture formation in an atmospheric optical LPP combustor. By employing naphthalene and fluoranthene, representing the middle and the high boiling fractions of typical aviation fuel, the fuel placement inside the premixing duct was characterised. In a different application a technique so called the laser sheet drop-sizing (LSD) was developed. This technique

used the ratio of the LIF to the Mie in order to estimate the droplet size of sprays. The results were in good agreement with PDA measurements. However, in addition to its 2D capability the LSD technique was presented as potentially applicable to dense sprays where PDA is likely to fail.

PLIF has also been applied in the study of mixture formation in spark ignition (SI) and diesel engines. Neij *et al.* (1994) used this technique to present quantitative results of the fuel-air ratio inside a research SI engine with an accuracy of about 10%. They used 3-pentanone as the fluorescence fuel marker. They observed large spatial and cyclic inhomogeneities in fuel concentration at the ignition time. The cyclic combustion variability was attributed to variations in the average fuel concentration close to the spark gap.

Hodges *et al.* (1991) applied PLIF to the study of the fuel jet dynamics of an evaporating and non combusting spray in a direct injection diesel engine. They used an exciplex combination and by appropriate selection of spectral filters reported semi-quantitative results on the gas and liquid phase concentrations of the spray. This technique was first developed by Melton & Verdieck (1985) who applied it qualitatively to the visualisation of the liquid and vapour phase of an evaporating spray.

3.10 Computational fluid dynamics (CFD) modelling

The design, development and testing of a new combustor is a lengthy process and can involve considerable cost. In the preliminary stage of the design however, CFD can be used qualitatively to assess the main features of a design. Modifications and geometry changes, at the preliminary simulation stage, can favour the choice of a design compared with a different one. Also, with the ever increasing computing power and improved models, complicated and detailed geometries are being studied. Nevertheless, since CFD models often are based on approximations, there is a constant need for validating those models against experiments.

Smiljanovski & Brehm (1999) used CFD analysis to study the steady state two-phase turbulent combusting flow in a single annular low NO_x combustor. The model was based on a RQL (rich-quench-lean burn) concept. Primary reduction of the emissions were achieved by experimental development of the fuel injector and the air ports hardware. For further reductions CFD was chosen to reduce the number of necessary but costly tests. Special attention was paid to the boundary conditions, particularly with respect to the fuel nozzle, and the grid density. The simulated case was for high power take off conditions and the results were compared with a the full annular rig tests. Although the temperature distribution and the NO_x emission index were satisfactory, the mixing prediction was found to be poor. They concluded that, the CFD should be used only on a qualitative basis for comparison of one design relative to another, by keeping all turbulence and model parameters identical.

Crocker *et al.* (1997) used a 2D axisymmetric CFD analysis of a fuel injection system with swirling flow. Prior to the simulations they considered carefully the inlet boundary conditions from correlation of the tangential velocity, pressure drop and blockage effects for each swirler. They concluded that their methodology allowed to predict the overall effective area of the fuel nozzle with good accuracy. Crocker *et al.* (1999) also used CFD modelling to predict the temperature contours at the exit of a combustor. The simulations were carried out for a 24 degree sector of the model combustor and were started from the compressor diffuser exit to the turbine inlet.

Stuttaford & Rubini (1997) used a network approach in the preliminary design of a gas turbine combustor. This method was based on the use of independent semi-empirical sub-flows describing the overall flow characteristics. The continuity equation and the pressure drop were solved by a pressure-correction methodology. In order to account for heat loss due to film cooling and annulus heat addition a full conjugate heat transfer model was developed. The combustion processes were simulated through an equilibrium calculation including the effect of mixing and recirculation. They concluded that the network solver predicts mass flow splits and pressure drops accurately within a combustor and that it is a versatile and accurate tool in the preliminary design of a gas turbine combustor.

3.11 Summary

An extensive survey of the literature revealed that there is relatively little information available on realistic gas turbine combustors. Atmospheric and high pressure tests are often carried out in model lean-premixed laboratory combustors burning gaseous fuel (relevant to industrial gas turbines). This is an evidence of the difficulty in making measurements in practical cases. However, non-intrusive diagnostic techniques are being developed and increasingly used by engine manufacturers.

It was also found that the most common methods of studying combustion parameters most often make use of PDA and PLIF. PDA has been widely used in characterising the injection properties of atomisers, whereas PLIF has found applications in species-selective and mixing characterisation studies, particularly with respect to the study of fuel placement in realistic devices. Unarguably, due to high spatial and temporal resolution, and 2D planar capability of the PLIF, it constitutes the method of choice for the study of mechanisms such as mixing and pollutant formation. This diagnostic tool was thus selected for the purpose of the present work. The fundamentals of LIF and a fluorescence signal calibration method are discussed in the next chapter.

Chapter 4

Fuel concentration calibration measurements

4.1 Introduction

As previously discussed, the study of the mixture formation in practical gas turbine combustors is of paramount importance. Therefore, quantitative measurements of AFR require a diagnostic technique which is instantaneous and provides a two-dimensional representation of this mixing. Measurement techniques which are intrusive or pointwise, such as probe sampling and CARS, are of limited interest. Other techniques such as, Raman and Rayleigh have weak cross sections and suffer from the presence of particles and the elastic scattering of the laser light. These are usually about 10^3 times stronger and limit the use of such techniques in realistic applications. Planar LIF, however, is perfectly suited for such measurements. It has a large cross section and can provide instantaneous and average species concentration measurements.

The calibration method for the determination of local equivalence ratio and fuel concentration, discussed in this chapter is based on this technique. To this end, the fundamentals of LIF are presented with a review of quantitative AFR measurements. Suitable fuel markers are identified and the calibration process of the fluorescence signal both for the vapour and the liquid phase, by purpose-made calibration devices, is detailed. The application and limitations of each calibration are discussed, with recommendations for improvements.

4.2 Fundamentals of LIF

Fluorescence is the process in which an atom or molecule emits radiation when it decays spontaneously from a higher to a lower energy level or state. The fluorescence can either occur at the same wavelength than the excitation (from the same level as in

absorption) in which case it is called *resonance fluorescence*, or at a different wavelength through new levels not involved during the absorption. Figure 4.1 illustrates a simplified two energy level diagram.

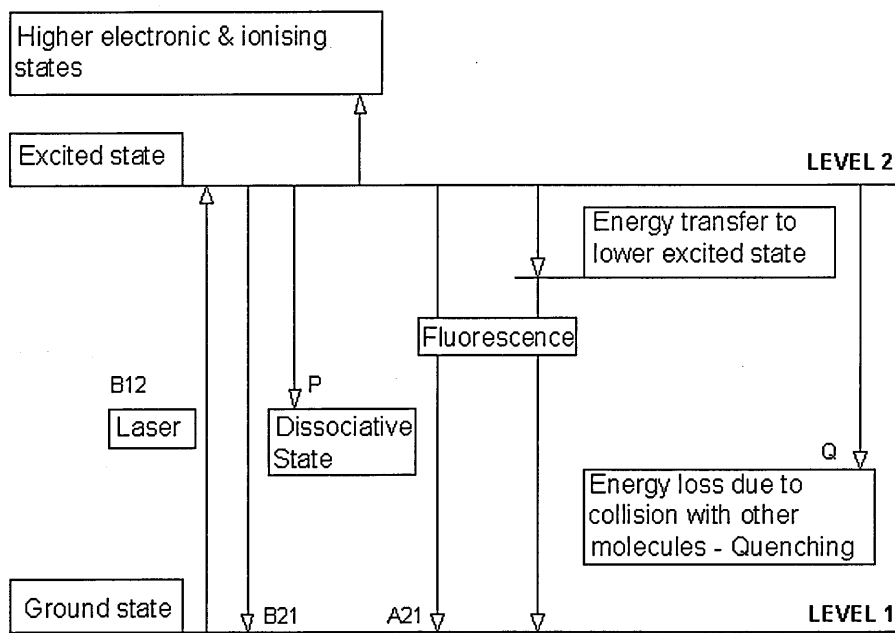


Figure 4.1 Two energy level diagram of fluorescence

The excited state, which is a result of laser photon absorption, can lose population and return to the ground state, by the following transitions. There can be spontaneous emission of a photon, i.e. fluorescence, the rate of which is determined by A_{21} . However, photo-ionisation is also possible by absorbing additional photons. The energy of the molecules or the atoms can increase to higher states or levels such that electrons are allowed to escape, creating an ionised state. Internal interaction of atoms in a molecule can lead to predissociation at a certain rate (P). Molecular collision within the excited state can also cause vibrational or rotational transition with emission of further fluorescence. The fluorescence is thus broad band and often red shifted. Finally, collision with other molecules can lead to transfer to ground electronic state, without radiation. This is termed quenching, the rate of which is determined by Q . In the above two energy level diagram B_{12} and B_{21} are respectively the Einstein coefficient for the stimulated excitation and emission rates, Q_{21} the quenching rate and

A_{21} the spontaneous emission rate. The rate of change of the population, for the laser spectral intensity I_v , of the lower and the upper level N_1 and N_2 can be expressed by:

$$\frac{dN_1}{dt} = -N_1 B_{12} I_v + N_2 (A_{21} + Q_{21} + B_{21} I_v) \quad (4.1)$$

$$\frac{dN_2}{dt} = N_1 B_{12} I_v - N_2 (A_{21} + Q_{21} + B_{21} I_v) \quad (4.2)$$

For steady state conditions (laser pulse duration is longer than the fluorescence lifetime) the above equations are equal to zero. With population conservation where N_0 is the initial total population at lower level, $N_0 = N_1 + N_2$, the population of the excited state can be written as:

$$N_2 = N_0 \frac{B_{12} I_v}{A_{21} + Q_{21} + (B_{12} + B_{21}) I_v} \quad (4.3)$$

If the saturation spectral intensity at wavelength v is defined as:

$$I_{\text{sat}}^v = \frac{A_{21} + Q_{21}}{B_{12} + B_{21}} \quad (4.4)$$

Then N_2 can be expressed as:

$$N_2 = N_0 \frac{B_{12}}{B_{12} + B_{21}} \frac{1}{\left(1 + \frac{I_{\text{sat}}^v}{I_v}\right)} \quad (4.5)$$

The fluorescence signal F_s is then proportional to the initial state population number density multiplied by a so-called fluorescence efficiency and can be expressed as:

$$F_s \approx N_0 \frac{B_{12}}{B_{12} + B_{21}} \frac{A_{21}}{\left(1 + \frac{I_{\text{sat}}^v}{I_v}\right)} \quad (4.6)$$

Assuming that the upper level is not predissociative, i.e. P is negligible (see Figure 4.1), and that the laser power is low, $I_v \ll I_{v,\text{sat}}$, the fluorescence can be written as:

$$F_s \approx N_0 B_{12} I_v \frac{A_{21}}{(A_{21} + Q_{21})} \quad (4.7)$$

The fluorescence is said to be in the linear regime, since the output is linearly proportional to the input laser intensity. If the laser intensity is much higher than the

saturation intensity, i.e. $I_v \gg I_{v,sat}$, then the fluorescence signal becomes independent of both initial laser intensity and quenching. Under this condition:

$$F_s \approx N_0 \frac{B_{12}}{(B_{12} + B_{21})} A_{21} \quad (4.8)$$

However, in practice A is typically smaller than Q and the quenching cannot be ignored. Thus, quantitative concentration measurement require the knowledge of the quenching rate, which is composition, pressure and temperature dependent. In unsteady combustion, given temperature and gas composition variations, all major collider species and temperature must be measured simultaneously with saturated LIF (LIFS). This can be achieved with Raman scattering but is restricted to clean flames only. Nevertheless, saturated fluorescence has limitations. Many hydrocarbons do not saturate at available excitation laser wavelengths. Besides, it is not possible to saturate the beam during its pulse duration since lasers often have approximately Gaussian spatial intensity distribution. This gives rise to simultaneous non-saturated, partially saturated and saturated fluorescence.

At low pressures Q can be determined from temporal decay of LIFS (Eckbreth, 1996). In general Q can be estimated from the steady-state approximation for the concentration of the excited state species. This procedure can be found in text books dealing with physical chemistry, for instance by Atkins (2000), and is detailed next. Consider the following scheme with their corresponding rate of reactions:



where S is an absorbing species, S^* an excited state, Q a quenching agent, I the excitation rate, k_f and k_Q the fluorescent and quenching constants, and $h\nu_i$ and $h\nu_f$ represent the incident and the fluorescent photons, respectively. The steady-state approximation for the concentration of S^* implies that:

$$\frac{d[S^*]}{dt} = I - (k_f + k_Q[Q])[S^*] = 0 \quad (4.12)$$

$$[S^*] = \frac{I}{k_f + k_Q[Q]} \quad (4.13)$$

The fluorescence intensity is proportional to $k_f[S^*]$, therefore

$$I_f \propto \frac{k_f I}{k_f + k_Q[Q]} \quad (4.14)$$

If the fluorescence intensity in the absence of Q is denoted as I_f^0 , it follows that

$$\frac{I_f^0}{I_f} = 1 + \frac{k_Q}{k_f} [Q] \quad (4.15)$$

where the ratio of k_Q to k_f is known as the Stern-Volmer coefficient. By plotting the left hand side of the equation 4.15 against $[Q]$, the Stern-Volmer coefficient can be determined. However, in order to distinguish k_f and k_Q the time constant of the fluorescence decay can be measured in a pulse experiment. The rate law immediately after a brief flash of radiation (laser pulse) forms an initial concentration of S^* given by:

$$\frac{d[S^*]}{dt} = -(k_f + k_Q[Q])[S^*] \quad (4.16)$$

The solution of this equation is given by

$$[S^*]_t = [S^*]_0 e^{\frac{-t}{\tau_f}} \quad \text{where} \quad \frac{1}{\tau_f} = k_f + k_Q[Q] \quad (4.17)$$

Therefore, a plot of $1/\tau_f$ (which can be obtained from the fluorescence intensity curve as a function of time) against $[Q]$ would yield k_f at $[Q]=0$ and k_Q as the slope.

4.3 Review of AFR measurements by PLIF

The following section is a review of some of the developments in planar LIF, which have been applied to the study of local AFR. Given the various processes involved in fluorescence, particularly quenching, attempts have been made to quantify for its effects. In other approaches, the use of a suitable dye, insensitive to quenching, bypasses the need for the evaluation of the quenching effect. In other cases calibration is carried out, allowing corrections of the measurements.

4.3.1 Fluorescence lifetime imaging

The quantitative determination of the local equivalence ratio, requires the knowledge of the local fuel and oxygen concentrations. In the absence of quenching, the fluorescence signal is proportional to the concentration of the fuel marker. When quenching is important the concentration of the quencher must be known too (Ni & Melton, 1991). The quenching of the total fluorescence signal by oxygen (the primary fluorescence quencher of organic molecules) can be expressed as:

$$\frac{I_0}{I} = 1 + K' [O_2] \quad (4.18)$$

I_0 and I correspond to the fluorescence signal in the absence and presence of oxygen. K' is the Stern-Volmer quenching coefficient such that for a given temperature $K' = k \cdot \tau_0$ where k is the bimolecular rate coefficient and τ_0 the collision-free radiative lifetime. If the molar concentration of the fluorescent tracer in the fuel-vapour is constant the fuel concentration is proportional to the unquenched fluorescence signal:

$$[\text{fuel}] = B \cdot I_0 \quad (4.19)$$

where B can be measured experimentally, against a known concentration of fuel. By combining equation 4.18 and 4.19, the fuel concentration can be expressed in terms of collected laser intensity and oxygen concentration.

$$[\text{fuel}] = B \cdot I \cdot (1 + K' [O_2]) \quad (4.20)$$

The Stern-Volmer equation can also be defined as:

$$\frac{\tau_0}{\tau} = 1 + K' [O_2] \quad (4.21)$$

Where τ_0 and τ are the unquenched and oxygen quenched fluorescence lifetimes respectively. If τ_0 and K' are known the measurement of τ will allow to determine the concentration of oxygen:

$$[O_2] = \frac{\left(\frac{\tau_0}{\tau} - 1 \right)}{K'} \quad (4.22)$$

By substituting this equation into 4.20 the fuel concentration can be expressed as:

$$[\text{fuel}] = B \cdot I \cdot (\tau_0 / \tau) \quad (4.23)$$

The local equivalence ratio can then be calculated, as shown in equation 4.24, where S is the fuel-oxygen-ratio for a stoichiometric mixture.

$$\Phi = \frac{1}{S} \frac{[\text{fuel}]}{[\text{O}_2]} = \frac{\text{BIK}'\tau_0}{S(\tau_0 - \tau)} \quad (4.24)$$

The above expression is only based on quenching by oxygen. Other species such as CO₂, H₂O and radicals can also contribute to the overall quenching. Since fluorescence is very short (typically a few nanoseconds), for fluorescence lifetime imaging to be successful, two fast dual gated image intensifiers must be used.

The fluorescence signal of the second image, taken a few nanoseconds later, can be used by appropriate calculations to yield the quenching factor. Although, the proof of concept has been demonstrated by Ni & Melton (1991) it is yet to be applied to a realistic case. The requirement for specialised equipment (short laser pulse and picosecond imaging resolution) has limited the use of fluorescence lifetime imaging (Eckbreth, 1996).

4.3.2 Exciplex fluorescence measurements

Exciplex is the name given to an **excited state complex** and can form when an organic molecule in the excited state binds with a different molecule in the ground level (Melton, 1993). Two organic molecules, M (the monomer) and G (the quencher) are mixed together. M can absorb light to form an excited singlet state M*. This excited molecule can react with the ground state partner G (usually at much lower concentration than M) to form an exciplex E*.



The attraction for exciplex is that it allows simultaneous liquid and gas visualisation. In the liquid phase M* and G bind readily while in vapour phase that likelihood is smaller. Therefore, in the liquid phase exciplex fluorescence is dominant whereas when vaporised, the monomer (M) fluorescence becomes dominant (higher concentration). Besides, since energy is required to create E*, the exciplex emission is red shifted. By selecting appropriate filters the fluorescence of the liquid and the vapour can be visualised separately. Exciplex fluorescence is however very sensitive to quenching

and its use has been limited primarily to non-combusting, oxygen-free environments. Despite limitations, calibrations have been attempted to present quantitative results.

Rotunno *et al.* (1990) first reported on a calibration procedure. They used a mixture of tetramethyl-p-phenylenediamine (TMPD) as the monomer and naphthalene as the quencher. Vapour phase calibration consisted of measuring the laser absorbance of TMPD vapour as a function of temperature. This was used to calculate the vapour concentration. The fluorescence of the vapour was then measured at that temperature. For the liquid phase, the fluorescence intensity was calibrated against droplets of known diameters. The fluorescence was shown to be proportional to the cubic of the diameters, necessary for quantifying the liquid.

Fröba *et al.* (1998) used a mixture of Triethylamine (TEA) and Benzene in a similar study applied to an internal combustion engine. They undertook an extensive calibration of the fluorescence signal as a function of temperature, AFR and pressures. It was found that the only quenching molecule was O₂ but since the fluorescence was a linear function of the AFR, quantitative measurements could be carried out.

Chojnacki & Feikema (1996) studied qualitatively the mixing of two liquids using an exciplex. Droplets containing cetane and naphthalene (M) were released into a container filled with cetane and TMPD (G). The interface was successfully visualised and it was concluded that this method can be applied to the study of liquid-liquid mixing. The desired fluorescence properties of an exciplex require a careful choice of concentrations for M and G.

4.3.3 Acetone fluorescence measurements

Acetone is widely used in a variety of experiments. The fluorescence yield of acetone is generally dominated by intersystem transfer and therefore is insensitive to quenching (Hanson, 1997).

Tait (1994) also studied the fluorescence of acetone in the presence of nitrogen and oxygen. Neither molecules were found to influence the fluorescence signal. However, it was found to be a function of temperature. Acetone PLIF was successfully applied to

the isothermal study of the local AFR, in a gas turbine combustor sector. Given the low evaporation temperature of acetone (boiling point 56.2 °C) the study was restricted to the vapour phase only. The fuel was assumed to be only present under gaseous form.

Bazile & Stepowski (1995) also used acetone in the study of liquid and vapour concentration fields of a burning spray jet. The fluorescence was found to be independent of the phase, thus allowing for separation between the contribution of the liquid and the vapour. The absorption of the UV (ultra-violet) light at 284 nm yielded a fluorescence signal which was proportional to the mass of acetone, in the vapour phase and function of droplet surface, in the liquid phase. The absorption coefficients and the fluorescence signal of vapour acetone were measured in a homogenous mixture. A stream of monosized droplets was used to calibrate the fluorescence of the liquid as a function of drop diameter.

4.3.4 Fluorescence flux measurements

Harding (1996) used naphthalene as fluorescent fuel marker to study the local AFR distribution of a LPP duct. The fuel was considered to be fully vaporised and that it had the same velocity as the surrounding air. The calibration was based on the integration of the fluorescent signal, of a mean image, correlated against the known initial condition of the overall AFR. The following expression was suggested to define AFR:

$$\text{Overall AFR} = \frac{m_a}{m_f} = \frac{\int 2.\pi.r.U_a[\text{air}]dr}{\int 2.\pi.r.U_f[\text{fuel}]dr} \propto \frac{1}{F_s} \quad (4.26)$$

Subscripts a and f refer to air and fuel respectively, U is the velocity (m/s) and m the mass flow (kg/s). Based on the assumption that the fluorescence was proportional to the fuel concentration, the overall AFR was related to the mean fluorescence signal spatially averaged across a processed image. However, this could only be achieved given detailed measurements of the velocity field characterised in previous experiments using LDA. The integration of the fluorescence signal along the premixing duct resulted in a 25% variation and was a measure of the accuracy of this method.

4.3.5 Summary

PLIF has been applied to a wide range of investigations in isothermal and combustive environments. The quantification and absolute concentration measurements of species have been, however restricted mainly due to the quenching of the fluorescence signal. It must be noted that quenching is of prime concern at elevated pressures and in reacting flows. Given the number of radicals and products of combustion which can interact with the fluorescent tracer, the correction for quenching by each colliding partner is very difficult. Nevertheless, various methods have been used to quantify PLIF imaging results. Therefore, despite quenching, at atmospheric pressure and in a non-reacting flow, it should be possible to undertake calibration experiments which can be correlated to an experimental case. Such a calibration is the adopted approach in the study of two LPP ducts and is discussed in the following sections.

4.4 Vapour-fuel visualisation strategy

The fluorescence signal calibration consists of correlating the fluorescence emission against known conditions of fuel concentrations. To this end, considerations on the choice of a suitable fuel marker are discussed. A vaporiser was designed for the above calibration and is described. The theoretical correlation which allows to determine the fuel concentration as a function of inlet parameters has been derived. The application and limitations of the present calibration method are also detailed.

4.4.1 Choice of a fuel tracer

In order to locate and visualise the spatial distribution of the fuel in a combustion device, a fluorescent tracer is added to the fuel. This tracer should have some properties which are described next:

- The tracer must be soluble in the fuel
- The tracer must be stable at operating temperatures of a gas turbine, i.e. does not undergo decomposition
- The concentration of the tracer must be such that it does not impact the physical properties of the fuel

- The tracer must possess similar properties relative to the fuel, in particular with respect to its vaporisation
- The fluorescence of the tracer should be sufficiently high with available excitation radiation
- The tracer must constitute an optically thin medium, as to avoid extensive absorption of the laser radiation
- The influence of quenching on the fluorescence should be as small as possible
- The fluorescence intensity should ideally be relatively independent of temperature and pressure.

The fuel which is used in aero-engine gas turbine applications is kerosene. It is made of compounds which have different boiling temperatures. Typically, kerosene boils between 150 °C and 325 °C. Besides, it contains aromatic rings which may vary in percentage from one batch to the other as observed by Harding (1996). Therefore, in order to avoid ambiguity as to the contribution of the fuel-tracer to the overall fluorescence a suitable substitute must be found. Potentially there are two candidates, namely mineral spirits (LeGal, 1999) and Exxsol D-80. They both are very similar to kerosene with the exception that their aromatics content is about 0.1% relative to 10-15% in kerosene. Exxsol D-80 is chosen in the present study as it is economically more attractive.

Ketones and aldehydes are often used as fluorescence seeds since they readily absorb laser excitation in the range of 220-320 nm. KrF and XeCl excimer lasers and Nd:YAG lasers can be used to this end. Their fluorescence is red shifted, 350-600 nm, and exhibit little sensitivity to quenching. One such example is acetone (dimethyl ketone). As discussed earlier, acetone has a very low b.p. (boiling point), thus it can not be used to track the vaporisation of the fuel in a gas turbine combustor. Since the vaporisation of acetone at high temperatures would be almost instantaneous, it can only be applied to a fully vaporised case.

In IC engines, acetaldehyde was found to be a suitable fuel marker since its fluorescence was independent of pressure at room temperature (Bryce, 1996). Berckmüller (1996) used 3-pentanone (diethyl-ketone) since it had very similar

vaporisation characteristics relative to isooctane. Toluene has also been reported in IC engines for AFR measurements (Cessou *et al.*, 2000). In a manner similar to acetone, the low boiling point of those markers limits their use in gas turbine applications. Therefore tracers with higher boiling points are required for the latter application.

In addition, since kerosene or its substitutes are multicomponent fuels, by selecting a tracer which has the mid-boiling fraction of the fuel, one can characterise the average evaporation and fuel distribution of a practical device. A survey of the aromatic molecules, as presented by Berlman (1971) revealed that the choices are restricted. Nevertheless, possible candidates for the study of the vapour-phase are naphthalene (b.p. 217 °C) and fluoranthene (b.p. 384 °C). Harding (1996) and Monmont (1999) both reported results using those markers. In both cases it was concluded that fluoranthene did not represent a realistic fuel placement within the premixing duct. The fuel was found to be near the duct walls, as a result of the swirl, and sometimes in contact with it. Higher concentration gradients were observed. On the other hand, naphthalene gave a more realistic picture of the fuel distribution.

Consequently, it was decided to use naphthalene, as fuel tracer, and Exxsol as fuel. Naphthalene absorbs strongly in the UV range and emits very strongly from 320 to 350 nm (Hicks *et al.*, 1997). Despite being sensitive to quenching naphthalene can be used in fluorescence calibration measurements. An adequate concentration of the seed to yield satisfactory SNR (signal-to-noise ratio) was found to be around 4%. The vapour-phase calibration and experiments are thus undertaken with exxsol mixed with 4% naphthalene by mass.

4.4.2 Description of calibration-vaporiser

The purpose of the calibration is to quantify the fluorescence intensity of the naphthalene against known conditions of AFR. In a realistic combustor the AFR distribution is far from being homogeneous. Also, they operate at high mass flow rates. Therefore, the calibration can be achieved with the use of a device which requires much smaller mass flows and has a satisfactory, near homogeneous AFR mixture for a given condition. To this end, a vaporiser had to be designed. Figure 4.2 is a picture of this vaporiser and shows its main elements.

The vaporiser is essentially made of a coil, an injection assembly and a U-shaped structure. The coil is a spiral of stainless steel pipe (about 6 m long) with an internal diameter of 6 mm and serves as a heater. By connecting the anode and cathode to a transformer it is possible to subject the coil to high currents. The heat which is generated in such a way, as a result of the resistance of the coil, is then used to increase the temperature of the air. This is a relatively economical way of achieving the latter. The air temperature can then be adjusted either by choosing an appropriate current or by adjusting the airflow. The positive and negative terminals can be interchanged when connecting to the main power supply. In order to prevent the current from heating the U-shaped structure, an isolation pad (Bakelite) and a ceramic stud are used to separate the two poles of the current supply. (Figure 4.2)

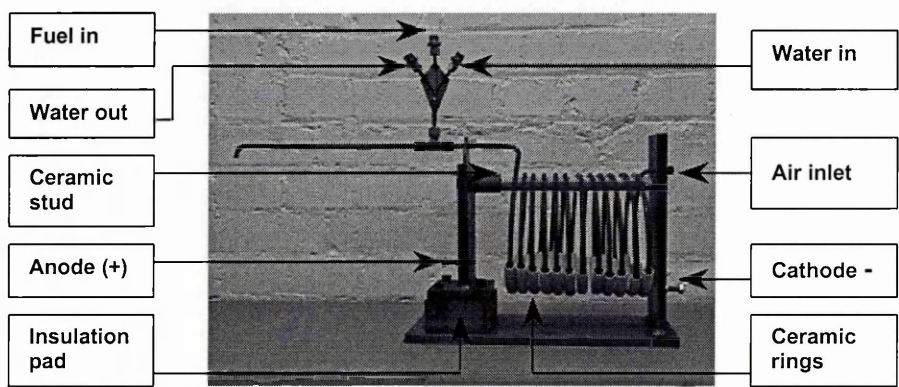


Figure 4.2 Vapour-phase calibration hardware

Additionally, ceramic rings are used around the lower part of the coil as to avoid creating “hot-spots” due to contact, when in operation. The fuel injection is achieved through a fine hypodermic pipe (0.5 mm in diameter). In order to prevent formation of carbon deposits it is water cooled. The injector tip can be in contact with air temperatures of up to 600 °C. Therefore, this protection was considered necessary. One advantage of having the T-junction assembly is that it can be attached to either end of the coil. For instance, if the vaporisation is insufficient it can be placed at the air entry level. This allows gradual heating of the fuel and subsequently complete vaporisation. The exit pipe can be used in a variety of ways. It can be set up to point downwards, upwards or axially, depending on the imaging requirements. Its length and diameter can also be varied as to obtain larger cross sections and provide a safe working distance relative to the hot coil.

4.4.3 Calibration of fluorescence-fuel-concentration

The fluorescence signal of naphthalene is to be correlated against known conditions of AFR, in other words fuel concentration. A simple analysis is carried out allowing to determine the latter as a function of inlet parameters, namely, temperature, fuel and air mass flows. Given the ideal gas law:

$$p = \left(\frac{n}{V} \right) \tilde{R} \cdot T \quad (4.27)$$

where p is the pressure, n number of fuel molecules (alternatively seed) per unit volume V , $\tilde{R}$ the universal molar gas constant and T the temperature. The total pressure can be defined as the sum of the fuel (subscript f) and air (subscript a) pressures, thus:

$$p_t = p_f + p_a \quad (4.28)$$

At a given temperature, provided the fuel is fully vaporised the temperature of air and fuel would be identical, therefore by applying equation 4.27 it can be shown that:

$$\frac{p_f}{p_a} = \frac{n_f}{n_a} \quad (4.29)$$

$$p_a = \left(\frac{n_a}{n_f} \right) p_f \quad (4.30)$$

By substituting equation 4.30 into 4.28, it can be written as:

$$p_t = p_f + \left(\frac{n_a}{n_f} \right) p_f \quad (4.31)$$

$$p_t = p_f \left(1 + \frac{n_a}{n_f} \right) \quad (4.32)$$

By applying the ideal gas law to the fuel, the partial fuel pressure can be expressed as:

$$p_f = \left(\frac{n_f}{V} \right) \tilde{R} \cdot T \quad (4.33)$$

Substituting this equation into 4.32 gives:

$$p_t = \left(\frac{n_f}{V} \right) \left(1 + \frac{n_a}{n_f} \right) \tilde{R}.T \quad (4.34)$$

If the concentration of the fuel in mol.m^{-3} is defined in terms of its number density then:

$$[\text{fuel}] = \frac{n_f}{V} \quad (4.35)$$

Finally this concentration can be expressed as a function of the inlet parameters:

$$[\text{fuel}] = \frac{p_t}{\left(1 + \frac{n_a}{n_f} \right) \tilde{R}.T} \quad (4.36)$$

But since the number of molecules can be related to the mass m and the molar Mass M , equation 4.36 can be modified using:

$$n = \frac{m}{M} \quad (4.37)$$

The fuel concentration is thus defined by:

$$[\text{fuel}] = \frac{p_t}{\left[1 + \left(\frac{M_f}{M_a} \cdot \frac{m_a}{m_f} \right) \right] \tilde{R}.T} \quad (4.38)$$

The fluorescence signal (F_s) can be directly correlated to the fuel number density through all the inlet parameters which are known. Inversely, in an experimental case the local AFR can be deduced from equation 4.38 such that:

$$\text{AFR}_{\text{local}} = \frac{m_a}{m_f} = \left[\left(\frac{p_t}{[\text{fuel}]_{F_s} \cdot \tilde{R}.T} \right) - 1 \right] \left(\frac{M_a}{M_f} \right) \quad (4.39)$$

The equivalence ration can then be calculated easily:

$$\Phi = \frac{\text{AFR}_{\text{stoichiometry}}}{\text{AFR}_{\text{local}}} = \frac{14.793}{\text{AFR}_{\text{local}}} \quad (4.40)$$

4.4.4 Control of calibration parameters

In order to create known conditions of AFR, an instrumentation of the vaporiser had to be carried out. Figure 4.3 illustrates schematically this arrangement. To heat the coil, a welding plant was used. It had two voltage settings with a whole range of current supply (amps). This was a versatile mean of adjusting the airflow temperature. However, this required a little time before thermal equilibrium could be established. The fuel line consisted of a pressure tank, a gas bottle, a flowmeter and a pressure gauge. The fuel tank was pressurised to 2-3 bars with either a nitrogen, helium or an argon gas bottle. Care was taken as to avoid mixing of this gas into the liquid fuel. To this end, the pressure was kept low and the tank was depressurised regularly.

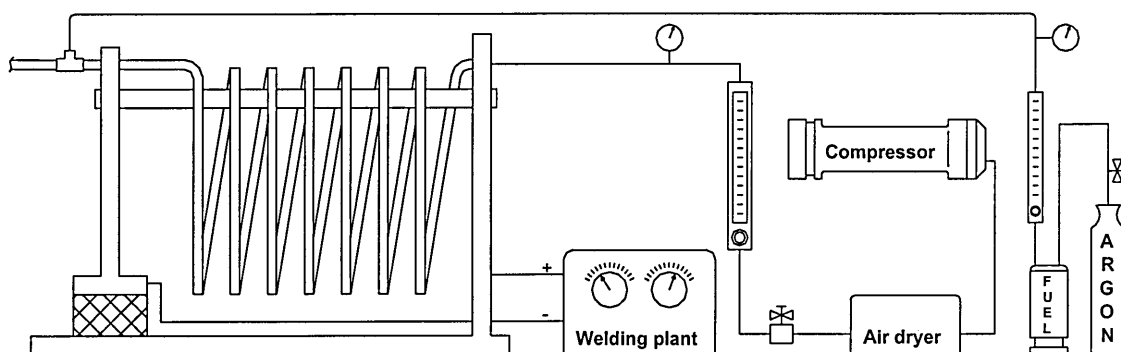


Figure 4.3 Instrumentation of the vaporiser

The flowmeter was also calibrated so that the fuel flow could be known. This calibration consisted of measuring the mass of the fuel, with a scale, at different reading levels. Samples were collected over periods of about 20-30 minutes for various opening of the flowmeter and the results expressed in terms of fuel flow (g.s^{-1}). With regard to the air supply, a different flowmeter was used. The mass flow of the air was calculated given the relationship provided by the manufacturer of the meter. A compressor was used to deliver the air. An air dryer was also employed to prevent the accumulated moisture of the air, released intermittently by the compressor, to cause fluctuations in the heated air temperature. Both the fuel and the air lines included a pressure gauge. The temperature of the mixture was measured at the exit of the pipe with a k-type thermocouple. With the use of a spreadsheet the inlet conditions were recorded for each experimental point in the calibration process.

4.5 Fluorescence imaging set-up

The fluorescence of the fuel marker is achieved through laser excitation and captured via a detection system. This section is a description of the basic equipment used in the calibration process and the experiments. Since two series of independent experiments were carried out during the present work, a typical set up would be presented here. Details of each experimental apparatus would be provide in relevant chapters.

4.5.1 Excimer laser

The bright emission of radiation from excimer lasers is in the ultra-violet region. An excimer is formed when an excited molecule bonds with the ground state molecule of the same species. Consequently, the term excimer is used for an excited homopolar molecule, whereas exciplex denotes an electronically excited heteropolar complex (the excited state bounds with a different species at the ground state). Examples of excimers and exciplexes are Kr_2^* , Ar_2^* and KrF^* , ArF^* and XeCl^* respectively. As a result, the excited molecule is formed by the interaction between two molecule (or atoms) one of which is in an excited state, i.e. $A + B^* \rightleftharpoons (AB)^*$. This excited molecule is unstable and decays to the ground state by dissociation. Since the lifetime of the bound upper state is much longer relative to that of the lower dissociative one (5 ns to 5 μs against 10^{-4} ns) population inversion is easily maintained. Excimer lasers can be tuned over a narrow range of frequency and have a broad spectral output of about 1 nm.

Figure 4.4 is a schematic representation of an excimer laser (adapted from the Lambda Physik catalogue). The excimer laser used during all the experiments was a Lambda Physik XeCl^* , model EMG 150 MSC, radiating at around 308 nm. Although it is strictly an exciplex it is referred to as an excimer. The laser has two independent cavities namely, the oscillator and the amplifier. The oscillator cavity contains a mixture gas made of a rare gas, a halogen and buffer gas. This mixture is pre-ionised and a discharge follows from the two electrodes of this cavity. The resonator of the oscillator is made of a holographic grating (G) and a partly reflecting mirror M1. The function of the prisms (P) is to expand the small laser beam so as to cover the full area of the grating. The grating is essential in the selection of the radiation wavelength, but also provides spectral condensation. The wavelength can be adjusted by altering the

position of the grater which causes a change in the incidence angle of the light on the grater. The laser light is then guided to the amplifier cavity by two aluminium coated mirrors (M2, M3).

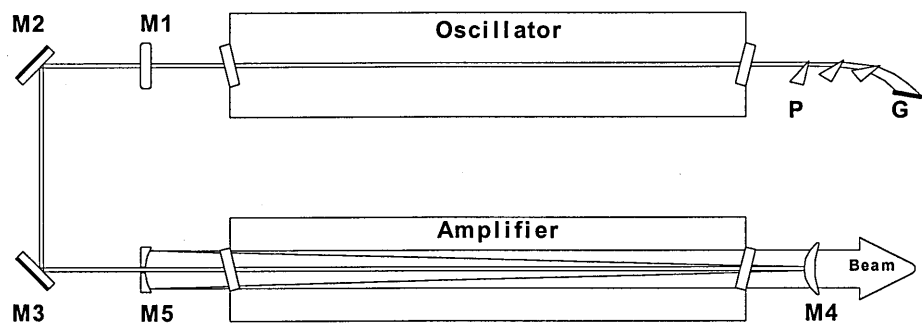


Figure 4.4 Schematic of an Excimer laser

The convex mirror (M4) and a concave reflecting mirror (M5) act as an unstable resonator optical arrangement. The laser light from the oscillator is injected into the amplifier through a small hole in M5. The central spot of mirror M4 is coated and is highly reflective. Thus, this laser light is reflected back, expanded and made parallel by concave mirror M5. The coated spot of M4 does not transmit the central part of the beam. This results in a small hole in the centre of the beam profile. The technical features of the excimer laser,

according to the manufacturer's specifications, are listed in table 4.1.

Lasing medium	XeCl
Wavelength	308 nm
Pulse energy	120-150 mJ
Beam shape	21x5 (mm x mm)
Pulse width (FWHM)	17 ns
Bandwidth (FWHM)	0.001 nm
Locking efficiency	90 %

Table 4.1 Technical specifications of the laser

4.5.2 Laser sheet

The laser sheet is generated by an arrangement of a spherical lens and two cylindrical lenses. The telescopic arrangement of the cylindrical lenses expands the beam to create a sheet with uniform thickness which is focused to a waist by the spherical lens.

The theoretical dimensions of the laser sheet are given by the following equations (Buchhave, 1994). The laser sheet thickness is:

$$t \approx \frac{4}{\pi} \sqrt{\frac{\ln 2}{2}} \frac{f_1 \lambda}{d_x} \quad (4.41)$$

where f_1 is the focal length of the spherical lens (L1), λ the laser wavelength and d_x the width of the laser beam. The focused sheet has an approximate length and height of:

$$\ell \approx \frac{8}{\pi} \frac{\lambda f_1^2}{d_x^2} \quad (4.42)$$

$$h \approx \left(\frac{f_3}{f_2} \right) d_y \quad (4.43)$$

where d_y is the height of the beam and f_2, f_3 the focal lengths of the cylindrical lenses (L2 and L3). The schematic of the optical arrangement is shown in Figure 4.5.

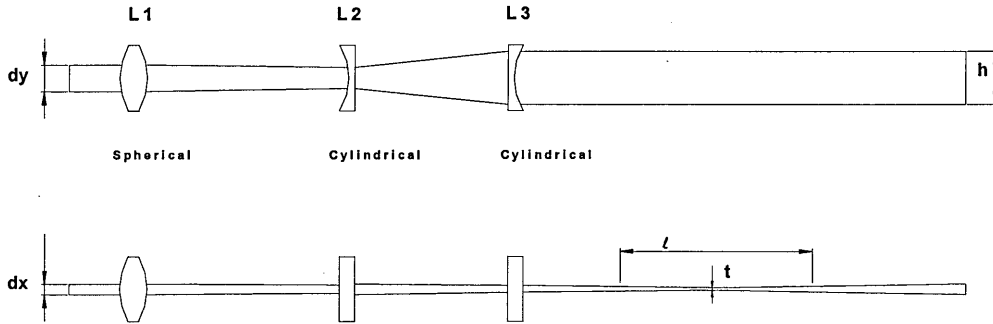


Figure 4.5 Laser sheet optics

With $\lambda = 308 \text{ nm}$, $f_1 = 2000 \text{ mm}$, $f_2 = -75 \text{ mm}$, $f_3 = 150$, $d_x = 5 \text{ mm}$ and $d_y = 21 \text{ mm}$, a typical laser sheet, formed in such a manner, would thus have a theoretical thickness of $t \approx 100 \mu\text{m}$, a length of about $\ell \approx 125 \text{ mm}$ and a height of $h \approx 42 \text{ mm}$.

However, in practice it is possible to adjust the distance between lenses L2 and L3 as to obtain a different laser sheet height and thickness to suit the experiments and to produce the required measurement volume.

4.5.3 Fluorescence detection

The fluorescence of the seed induced by the excitation of the laser sheet is usually collected at right angles by an imaging lens. This fluorescence is then directed to an image intensifier which is coupled to a two-dimensional detector array. Such an arrangement is referred to as an ICCD (intensified charge-coupled device) detector. The lenses used for calibration and experiments were either a 50 mm glass lens, NIKON f/1.2 coupled with a 1.4 tele-converter (for magnification) or a 105 mm NIKON, UV-lens f/4.5 when Mie scattering measurements were carried out. Since naphthalene fluorescence is essentially above 350 nm, the use of the glass lens filters the unwanted inelastic scattering, whereas the UV-lens allows detection of the latter. The choice of the lens was dependent upon the nature of the experiments and would be detailed later in this chapter. The schematic of an ICCD detector is illustrated in Figure 4.6

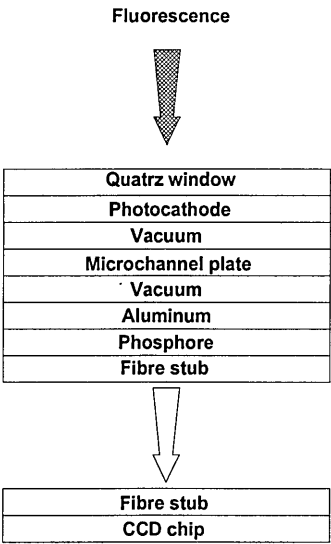


Figure 4.6 Schematic of an ICCD detector

The fluorescence is first formed on the photocathode which converts photons to electrons. These electrons can then be accelerated towards the microchannel plate (MCP) by gating the photocathode potential. A very high temporal resolution can be achieved by the use of fast gating. The MCP consists of a perforated plate with a large number of very small holes. Each electron, passing through each channel produces two or three additional electrons, as a result of contact with the channel walls. The gain of the MCP can be varied by adjusting the voltage applied across the plate. These

electrons upon exiting the MCP are accelerated towards a phosphor screen where they are converted back into photons. The use of image intensifiers is attractive for several reasons. They allow short electronically controlled exposure times, down to a few nanoseconds, which is not possible by mechanical shutters. In addition, it operates as a photon converter in the green wavelength region where the detectors are highly sensitive. Finally, the fluorescence signal is intensified to levels which can be detected by the CCD detector. The coupling between the intensifier and the CCD is achieved by using fibre-optics. The CCD chip is made of very small elements called pixels and is an integrated circuit. It possesses discrete potential wells in which electrons are trapped. Upon exposure, an amplifier measures the charge in each of the potential wells and converts this voltage into an output signal in terms of counts per pixel. The ICCD detector used in this work was a Princeton Instrument (PI) camera with a CCD chip of 576x384 pixels.

4.5.4 Synchronisation

In order to capture the fluorescence, a timing sequence is needed so that the exposure of the ICCD detector and the laser excitation coincide. This timing also allows to discriminate against unwanted signal such as flame luminosity. The excimer laser has a typical delay of about 1400 ns between the trigger pulse and the laser pulse. The latter has a duration of about 17 ns. In the case of imaging the fluorescence of naphthalene (lifetime of 96 ns) the intensifier can be gated for 100 ns. Since two different imaging set up were used during the present work, two different synchronisations and timing sequences were used.

In the first one the laser was used as master (commanding the sequence). A synchronised output pulse from the laser connected to a pulse generator activated the CCD chip and the MCP (intensifier). The gate width was 100 ns with a delay of 1400 ns. In the second arrangement a pulse generator triggered the laser which in turn similarly controlled the gating time and the delay sequence. The ICCD camera was also connected to a computer in which the exposure time of the CCD chip was set to an appropriate value. In the first case the laser was operated at 20 Hz and the exposure time was 1s and in the second it was operated at 1 Hz with an exposure time of 10 ms. The detail of each set up would be developed in the relevant part of the calibration or the experimental work.

4.6 Vapour-fuel concentration calibration

This section is a brief description of the vapour-phase calibration experiments which were used to determine the relationship between the fluorescence signal, temperature and fuel concentration. It also provides the description of a dual imaging set up to assess the degree of the vaporisation, important in the overall accuracy of this calibration experiment. The application and limitations of this method are specified and a suggestion for improvement is made.

4.6.1 Experimental set up

The experimental set up is illustrated schematically in Figure 4.7. The laser sheet is formed through a telescopic arrangement. However, due to the height of the laser a periscope had to be used to direct the beam to a lower level (this arrangement is not shown). This was then expanded to form the sheet with an approximate height of 30 mm. The outlet pipe of the vaporiser was placed at the waist level of the laser sheet. The fuel and the air supply were controlled, as described, by using flowmeters. The desired temperature of the flow was achieved by adjusting the current delivery from the transformer of the welding plant.

The fluorescence detection system consisted of a PI intensified camera, 384x576 pixels, with a 16 bit resolution. The glass lens used is a 50 mm NIKON f/1.2 combined with a 1.4 magnifier. The laser operates at 20 Hz and a synchronised output, with each trigger pulse, was directed to a pulse generator (PG 200). The gate width of 100 ns, set on the PG 200, activates the MCP control box which in turn operates the intensifier. The delay, in this sequence, is set to 1400 ns so that the "opening" of the intensifier and the fluorescence coincide.

The exposure time of the CCD chip was set to 1 second. This allowed to collect 20 images on the chip and hence increase significantly the signal to noise ratio (SNR). Since the laser was used as master, firing continuously, it was necessary to control the camera during data transfer to the hard disc of the computer. A signal from the PG 200 was sent to the Not-Scan connector of the camera. This also prevented the camera and the intensifier from functioning while no data acquisition was in progress or requested. The laser however, was switched on and off manually.

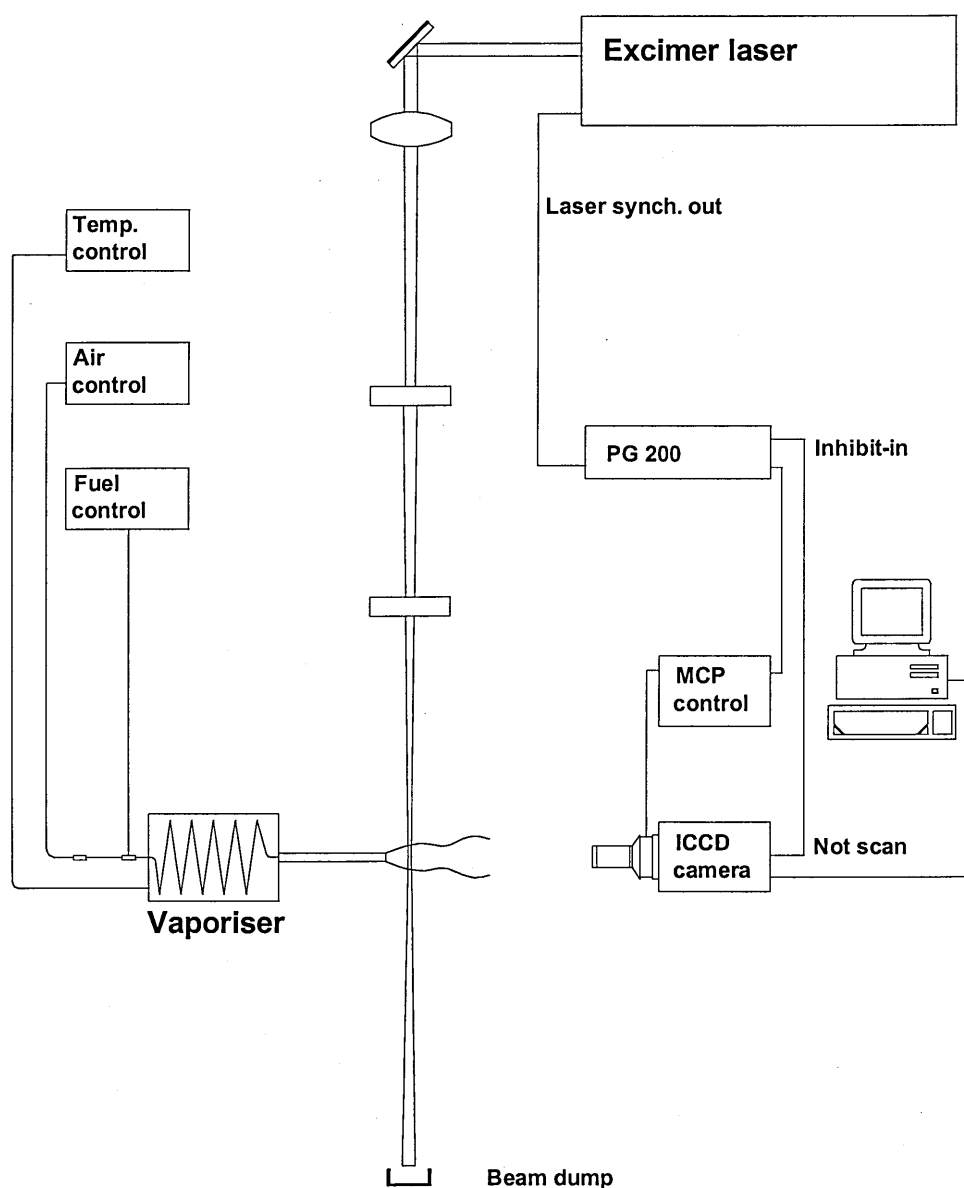


Figure 4.7 Schematic of vapour-phase calibration set up

4.6.2 Preliminary calibration results

With the use of the above set up the fluorescence was measured for a range of conditions, FAR and temperatures. The fluorescence signal was an average of 400 laser shots. It is selected in a small region of the jet (10x5 pixel) where the temperature was measured using a k-type thermocouple. Figure 4.8 shows the vaporiser operating at a fairly high temperature.

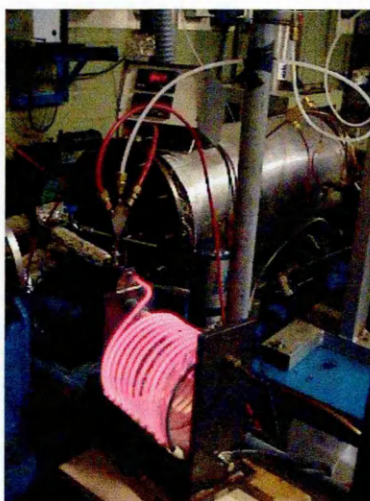


Figure 4.8 A typical vapour-phase calibration experiment

In a preliminary examination the influence of temperature on the fluorescence was assessed. The fuel concentration (number density) was kept constant while the temperature was varied. It was found that this relationship was linear over a limited range of temperature, as shown in Figure 4.9. The concentration is indicated in millimols per cubic meter and the fluorescence in terms of arbitrary units (a.u.).

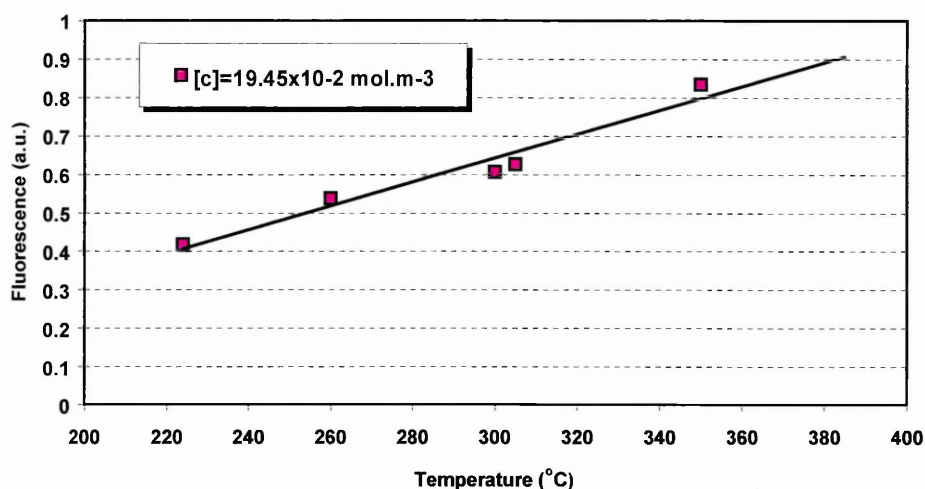


Figure 4.9 Fluorescence of Naphthalene at constant mixture concentration

An more detailed set of measurements were carried out, where both the temperature and the fuel concentration were varied. The results are shown in Figure 4.10.

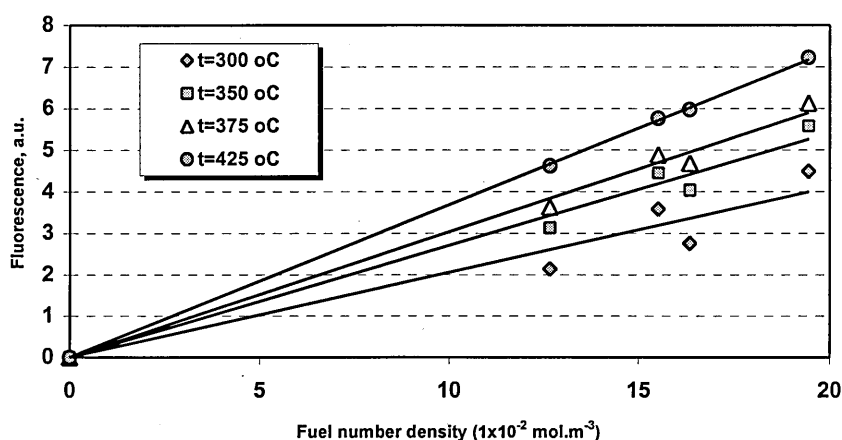


Figure 4.10 Fluorescence versus temperature and fuel concentration

Since it was found that the fluorescence signal was a linear function of the temperature it would be possible to interpolate the slope of the lines. This in turn would allow to obtain a value which would correspond to an actual operating temperature of a LPP module.

4.6.3 Simultaneous PLIF-Mie imaging

In order to assess qualitatively the degree of fuel vaporisation dual imaging was used. Simultaneous LIF and Mie imaging allowed the elastic scattering of light from particles, i.e. liquid droplets, to be collected. The set up was similar to the preliminary study but incorporated a set of mirrors arranged as shown in Figure 4.11. It makes use of two broadband aluminium coated mirrors and two 308 nm reflective mirrors. The elastic scattering is reflected by those mirrors whereas the fluorescence is transmitted through. Since the Mie signal was to be observed, a UV-lens had to be used. (NIKON 105 mm, f/4.5). When the fuel injection assembly was placed at the exit of the air flow pipe, particularly at low temperatures of about 220°C , Mie scattering was observed. This was evidence of the fact that the fuel was not entirely vaporised. Therefore the fuel was injected at the air pipe entry to allow better vaporisation. In this configuration no Mie signal was detected over the whole range of the calibration experiments, even at low temperatures. Consequently, the final calibration was carried out in this configuration. Besides, no sign of decomposition of naphthalene was observed as the signal response increased linearly with temperature and concentration.

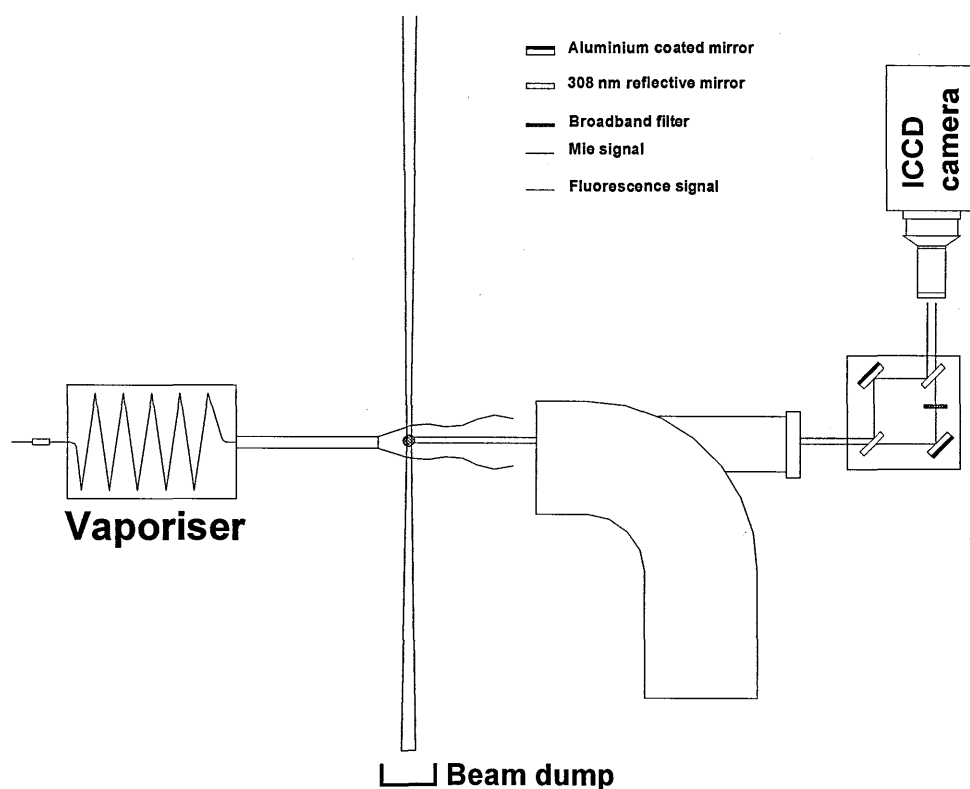


Figure 4.11 Dual imaging set up

As a result a more accurate set of calibration curves was obtained and is shown next.

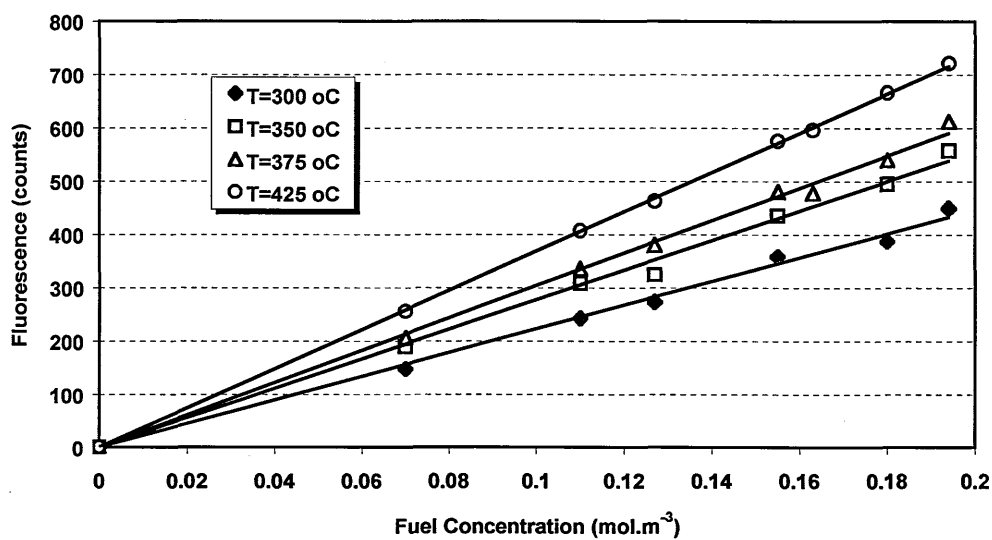


Figure 4.12 Improved signal calibration result

4.6.4 Calibration accuracy and limitations

As discussed earlier quenching is the main factor in limiting quantitative PLIF measurements. However, this is a severe problem at high pressures and in combusting environments. This calibration has therefore been derived for isothermal flows at or near atmospheric pressures. In addition, since the calibration is carried out using air, any possible quenching primarily due to O_2 (but also N_2) is accounted for. Moreover, this calibration is undertaken for a wide range of overall equivalence ratios and temperatures. There is therefore a direct relationship between the fuel concentration, the oxygen concentration (air-fuel ratio) and the fluorescence signal. The knowledge of the temperature field and the measured fluorescence signal, in a practical device, would enable accurate prediction of the local fuel concentrations and subsequently the local equivalence ratios. Nevertheless, in a practical device the overall working pressure is usually higher than atmospheric (unless if the measurements are carried out at the exit of the device – see for instance the small engine LPP duct in the next chapter). Therefore, the effect of quenching would be slightly stronger than that of the calibration phase. This difference is however small and is assumed to be negligible since a small increase in the pressure (typically 4%) would increase slightly the likelihood of the fluorescence molecules colliding with the quenching molecules.

The second factor which influences the accuracy of the calibration process is the attenuation of the laser power across the measurement plane. If the concentration of the fluorescent dye is such that a large proportion of the laser sheet is absorbed at the incident side (where the laser sheet enters the flow), then the measurements can not be considered as reliable. This is particularly true in liquid solutions and less of a concern in fully vaporised mixtures. In addition, the calibration measurements were carried out at the exit of a small pipe where the variation of the fluorescence signal along the path of the incident laser light did not vary in such a way as to suggest noticeable absorption. Figure 4.13 shows the influence of the laser power on the fluorescence signal ($T_{air}=350\text{ }^{\circ}\text{C}$ and $\phi=0.35$) which is a linear function. For a given experimental set up, the laser sheet used in the calibration and the experiments must be identical. Since in the experimental case the measurement plane is larger than that of the calibration, the laser sheet will be attenuated to a higher degree. Nevertheless, in the present study the effect of the laser sheet attenuation is considered to be negligible

since a weak concentration of the vaporised fluorescent dye (4% naphthalene by mass) was employed.

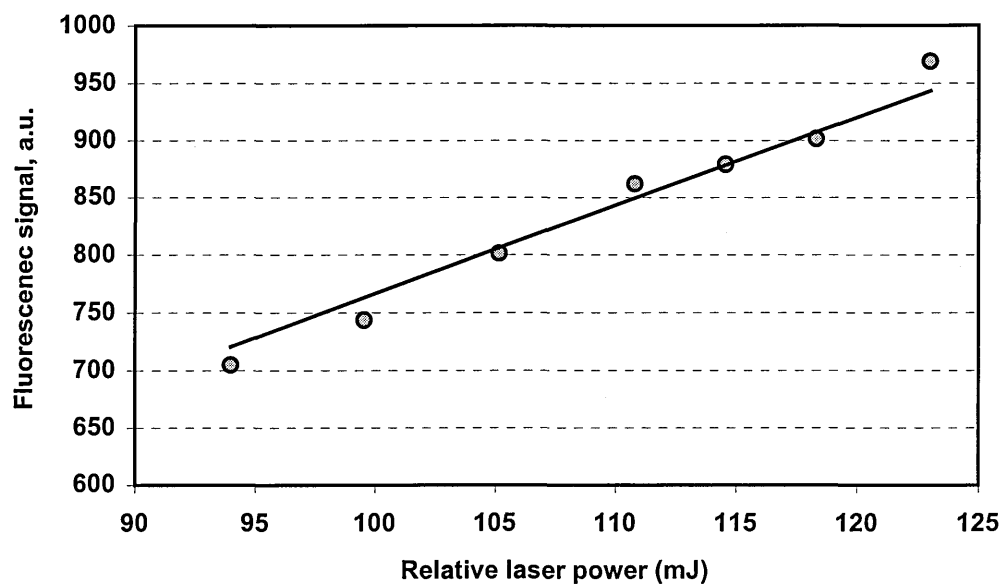


Figure 4.13 Influence of laser power on the fluorescence signal

Finally, the concentration profile of the dye at the exit of the calibration pipe is of paramount importance. As explained earlier, the fluorescence signal was measured in a small region at the centre of the jet. This was intended to prevent measurements where the surrounding air would not only lower the temperature of the flow but will result in a more dilute mixture (with lower equivalence ratios). It was also assumed that this mixture was homogeneous so that the local and the overall inlet equivalence ratio could be considered identical. This assumption is reasonable in the case of a turbulent flow. Indeed, in a laminar flow the velocity profile in a pipe has a parabolic shape (due to the boundary layer). It follows that for a given inlet fuel concentration the centre of the pipe will contain relatively a higher concentration of the fuel, resulting in inaccurate correlation of the local and the overall equivalence ratios. However, in the calibration experiments the typical Reynolds numbers were between 13000 and 18000, thus the flow was assumed to be turbulent. The velocity profile in the pipe is much flatter (in a turbulent case) resulting in a more constant mixture concentration.

A possible improvement to the current system can be achieved by supplying a co-flow of heated air or nitrogen to the jet (at the exit of the calibration pipe). This would prevent ambient air to diffuse into the outer edges of the jet, and decrease the temperature, thus reducing the fluorescence. In the present calibration this is not a problem, since the centre of jet is used for measurements. The usefulness of this approach would be to assess the variation of the fluorescence signal, over the cross section of the pipe, as to quantify the mixedness of the air-fuel in the jet. It is thus assumed that the mixture in the calibration case is near homogeneous.

The application and limitations of the this calibration method can be summarised as:

- The flow is isothermal, i.e. non-reacting.
- The temperature gradients are not large. The knowledge of the average temperature in the field is necessary to correlate fuel concentration to fluorescence.
- The calibration is only valid at atmospheric pressure. Higher pressure calibrations are possible but would require modification to the vaporiser (optical access into a section of the pipe prior to exit)
- The fluorescence signal, in addition to temperature and fuel concentration, is a function of laser power, optical set up, collection efficiency (camera layout) etc. Thus for each experimental case a unique calibration must be carried out.
- The calibration is applicable to systems with a reasonably good vaporisation, as to avoid interference and overlap from liquid fluorescence.

The exact accuracy of the present calibration is difficult to quantify without the above recommended modification. However, during all experiments utmost care was taken to ensure stable fuel and air flows to minimise fluctuations. A speculative indication of the calibration accuracy, based on the above, is believed to be around 5-10%.

4.7 Liquid-fuel concentration calibration

In a similar manner to vapour-fuel visualisation, with the choice of a suitable seed it is possible to visualise the liquid fuel fluorescence. An attempt for a “semi-quantitative”

measurement of the liquid phase was made and presented in this section. However, this constitutes a very challenging task in terms of laser diagnostics. To start, a brief overview of the methods applied to the study of the liquid phase is reported. The choice and the concentration of the seed is then determined as to obtain specific fluorescence properties. A preliminary experiment revealed a strong temperature dependence of the fluorescence signal. The limitations and the need for fundamental investigation of the fluorescence behaviour are highlighted.

4.7.1 Overview of liquid phase studies

PDA has been widely used for the study of droplet size and velocity measurements. Liquid volume flux measurements are also possible and reported with this method. However they are subject to large uncertainties (Trichet & Bismes, 1995). The main factors limiting the accuracy of the latter are defining accurately the measurement volume and the number of droplets passing through it. With PDA only one particle at a time can be present in the measurement volume and must be spherical in shape. If two or more particles are found in the measurement volume the signal is rejected. Therefore, algorithms must be used to correct for the probability of particle rejection (Brandt *et al.*, 1996).

Rotunno *et al.* (1990) also reported on quantitative measurements of the liquid mass of an evaporating fuel spray. This consisted on the choice of an exciplex with careful selection of the percentage of the monomer and the quencher. Although, the calibration was undertaken in a non-evaporating spray the results were used for an evaporating case. However, the fluorescence yield of the liquid phase was shown to be a linear function of the d^3 (d is the diameter of the droplet). They estimated the overall accuracy of their measurements to be $\pm 30\%$.

Harding (1996) used PPO (2,5 Diphenyloxazole) mixed in mineral spirits to qualitatively study the liquid fuel dispersion in a LPP duct. PPO was found to fluoresce strongly in the liquid phase. Nevertheless, at high temperatures the signal levels were much weaker. This was believed to be either due to quenching or decomposition of the PPO molecules. Monmont (1999) used azulene in a similar study. Due to strong

fluorescence in the liquid compared with the vapour phase, it was used to track the break up of liquid jets.

Bazile & Stepowski (1995) studied the fluorescence of acetone droplets and proposed a general expression for the latter. The fluorescence of the large and small droplets were anticipated to be proportional to d^3 and d^2 respectively. Nevertheless, the calibration of the fluorescence, for droplets in the range of 120 to 450 μm , was found to be proportional to $d^{1.57}$. This deviation from d^2 was assumed to be due to refraction and reflections on the surface of the droplet. They concluded that this relationship was less reliable than the mass dependence of the fluorescence signal in the vapour phase. In addition, laser sheet extinction by absorption was found to be another limiting factor in the quantitative measurement of the liquid fuel concentration. As a result, the fluorescence of droplets on the instantaneous images were removed so that the average vapour phase concentration could be determined.

More recently studies have focused on drop size measurements by combining simultaneous PLIF-Mie imaging. By rationing the fluorescence and the Mie signals a proportional expression for the SMD (Sauter mean diameter) was obtained and was a representation of volume to surface area ratios of the droplets. Nevertheless, only weakly absorbing droplets yield a d^3 dependence of the fluorescence signal. Where this absorption is important the latter is proportional to the drop cross sectional area rather than its volume (Zaller *et al.*, 1999).

Le Gal (1999) in a development of this technique reported results in excellent agreement with PDA measurements. An extensive study of the fluorescence signal as a function of dye concentration was carried out. PTP (p-Terphenyl) was chosen as a liquid fluorescence dye diluted in mineral spirits. A vibrating orifice droplet generator was used to provide a stream of monodisperse droplets. By comparing the signals of different solutions of PTP, containing different concentrations, the LIF and the Mie signals were measured as a function of the droplet diameters. It was found that a solution of PTP with 0.023 g.l⁻¹ in mineral spirits resulted in a fluorescence signal proportional to d^3 and Mie signal proportional to d^2 . This was successfully used in experiments of planar drop sizing applied to sprays.

4.7.2 Choice of a marker and its concentration

For similar reasons to those explained in Section 4.4.1, azulene is the best candidate for the study of the liquid phase in gas turbine environments. As shown by Monmont (1999) it has a very strong signal in the liquid phase and its fluorescence in the gaseous phase is negligible. In addition, it has a boiling point of 242 °C and can represent the mid-boiling point fraction of the aviation fuel. It also is fairly insensitive to quenching by oxygen (Berlman, 1971).

Therefore, by carefully selecting the concentration of the azulene it should be possible to obtain a fluorescence signal which is proportional to the volume of a given solution. As it was discussed, only weakly absorbing solutions yield such a relationship. Consequently, the concentration of the PTP (0.023 g.l⁻¹) in mineral spirits is used as a reference for determining that of the azulene in Exxsol D 80. Mineral spirits and Exxsol have similar fluorescence properties and can thus be substituted (LeGal, 1999).

The theoretical behaviour of light absorption through a medium can be expressed by the Beer-Lambert's law (equation 4.44). In the case of fluorescence, whenever the energy difference of two levels are equal to that of the emitted photon, a fraction of the excitation laser light is absorbed.

$$I = I_0 e^{-\epsilon c d} \quad (4.44)$$

where I_0 is the incident light energy, I the energy traversing through the distance d (path length), c the concentration and ϵ is the molecular absorptivity or molecular extinction coefficient. Therefore, for higher concentrations the absorption would be stronger. Based on this expression the absorbance is defined as (Parker, 1968):

$$A = \epsilon c d = \log_{10} \left(\frac{I_0}{I} \right) \quad (4.45)$$

The absorbance is thus proportional to the concentration of the absorbing species.

The measurements carried out by LeGal (1999) were undertaken at a laser excitation wavelength of $\lambda=266$ nm. Since the available excitation source for the current study was an excimer laser ($\lambda=308$ nm) and the fluorescent dye was different, the

absorbance of both solutions were to be matched. This was achieved by using a spectrometer (Elmer Perkin model RF – 5101PC). A fresh solution of mineral spirits containing 0.023 g.l⁻¹ of PTP was prepared. Several solutions of exxsol containing azulene with different concentrations were also prepared. The optical path lengths of both samples were identical since a 10x10 mm quartz cuvette was used. A similar absorbance was achieved with a solution of exxsol containing 0.0352 % azulene by mass for both solutions at 308 nm. The result of the absorbance adjustment with the spectrometer is shown in Figure 4.14. The absorbance of the PTP solution at 266 nm was 2.632. This was in good agreement with the value of 2.738 observed by LeGal (1999). However, this difference of less than 4% was possibly due to a difference in the nominal concentration of the newly prepared solution of PTP.

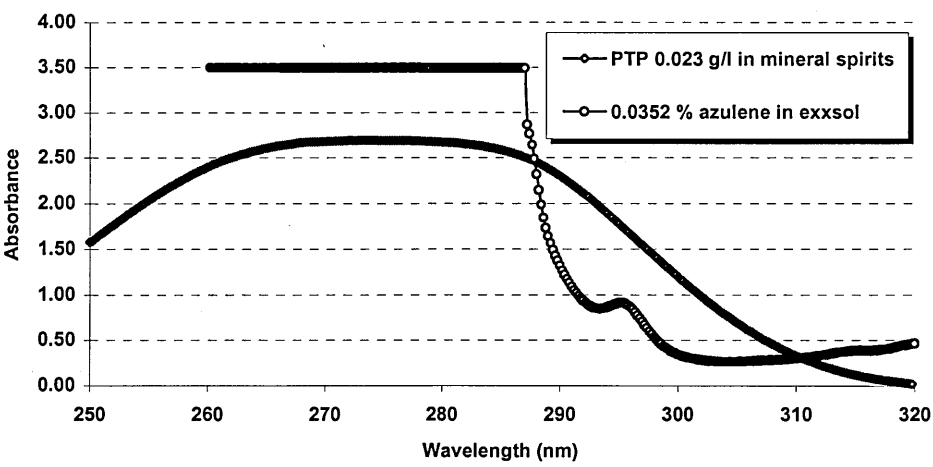


Figure 4.14 Concentration determination by absorbance adjustment

It was hoped that this solution of azulene would yield a fluorescence signal proportional to the volume as observed by LeGal (1999). A calibration experiment was carried out to assess the fluorescence behaviour of this solution and is the subject of the next section.

4.7.3 Fluorescence calibration measurements

The study of the liquid phase in a realistic device is often carried out for relatively large cross sections, e.g. a premixing duct. Therefore rather than spatially resolving a droplet

to study its fluorescence an alternative method of calibration was needed. In this instance, a known cross section of liquid injected into a laser sheet with a known thickness was the basis of the above measurements.

The calibration device consisted of a series of fine hypodermic needles which were used to inject the solution of azulene and exxsol. More precisely three “tubes” with internal diameters of 0.254, 0.33 and 0.51 mm were selected. The strong fluorescence of the azulene at room temperature created at first a total saturation of the CCD chip. Therefore, a neutral density filter (ND=1) was used to overcome this problem. This reduced the signal level by a factor of 10, which was readjusted in subsequent interpretation of the results. Since the cross section of each pipe was known, the fluorescence could be related to the volume of the liquid by determining the thickness of the laser sheet. The experimental set up was similar to the one illustrated in Figure 4.7. The tubes were attached to a traverse and positioned in the middle of the laser sheet. Only a pressurised fuel tank was used to supply the solution.

The measurement of the laser sheet thickness was first attempted by using a photodiode array. This consisted of a single row of 1024 pixels with a 10 bit digital resolution. It was placed such that it was facing the laser sheet at right angle. A series of neutral density filters were also positioned in front of the array as to avoid laser damage by reducing the transmitted power. Unfortunately, despite a few trials no signal was recorded on the pixels. It was thus assumed that in-built protection layer of the pixels was made of glass, filtering effectively the UV-laser light.

Consequently, a more conventional approach was adopted in the measurement of the laser sheet thickness. This approach made use of two adjustable slits to achieve the latter. While the slits impinged on the laser sheet a clear diffraction pattern could be observed on a piece of paper placed behind the slits. In addition, an energy meter was also used to monitor the increase in the laser power with increased opening of the slits. This distance was increased until the diffraction patterns faded and that the energy level reached a maximum. It was concluded that the laser sheet thickness was about 300 to 320 μm . For the liquid volume measurements a thickness of 320 μm is assumed to correspond more accurately to the real thickness of the sheet.

Since the cross section of the pipes and the laser sheet thickness are known, the volume of the liquid in the measurement volume could be easily worked out. In addition, given the density of the liquid ($\rho=0.780 \text{ kg.l}^{-1}$) the fluorescence could be directly related to the mass of the liquid. The result of this calibration, at room temperature, is shown next.

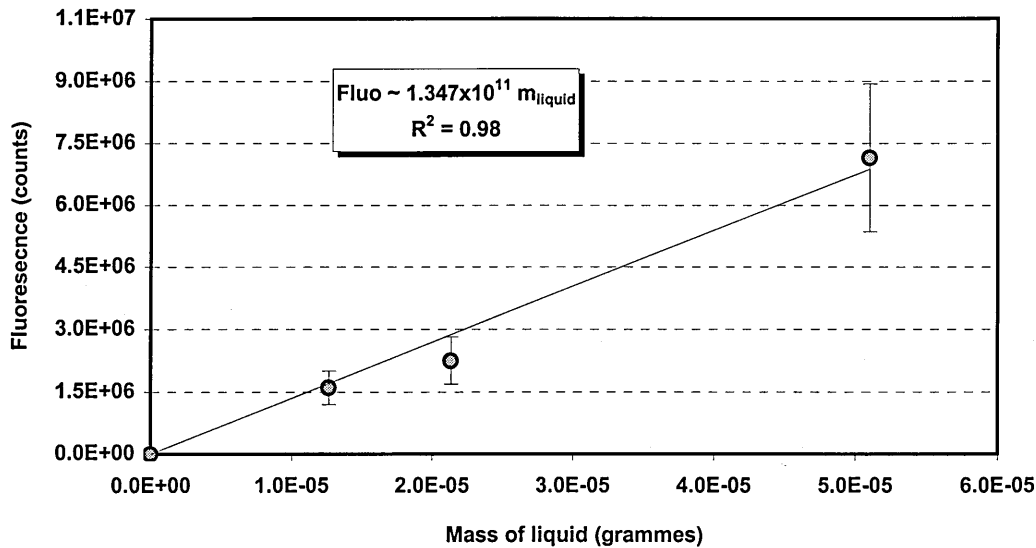


Figure 4.15 Fluorescence of azulene as a function of liquid mass

The fluorescence of each liquid jet is an average of 50 laser shots. The illuminated pixels of the CCD chip were summed in a square region, after background removal. The overall signal was then multiplied by 10 to account for the attenuation of the light by the neutral density filter. However, the repeatability of these experiments were difficult to achieve. A signal variation of $\pm 25\%$ was observed with slight variations in the positioning of the pipes. The inclination effect of the needle pipes on the variation of the liquid volume intersecting with the laser sheet was investigated by a 3D CAD analysis. On average, an inclination of 10 degrees resulted in an increase of 0.8% in the overall volume traversing the laser sheet (for the largest pipe). This increase is a result of the elliptical cross section in an inclined position compared with a circular cross section when the jet is perpendicular to the laser sheet. Therefore the misalignments due to the positioning of the pipe are not thought to affect the above variations to a large extent. A possible explanation for those variations may be associated with the optical and lensing effects of the laser light due to misalignments. These effects were reviewed by Hill & Bener (1988) and are referred to as morphology

dependant resonances (MDR's). The reflection of the laser light in the internal volume can produce constructive and destructive interference patterns. These may change from one setup to the other and thus result in a different level of fluorescence signal.

4.7.4 Preliminary liquid-phase study

With the use of the same imaging set up a preliminary investigation of the fluorescence signal in a realistic device at elevated temperature was carried out. A pressure jet injector with 5 holes (diameter 0.35) injected the liquid into the heated air stream. The average fuel flow was about 2 g.s⁻¹ and measurements were carried out at 15 mm downstream the exit of a prefilmer (45 mm relative to the injection point). The swirling motion of the air entrained the liquid in such a way that the liquid was visible by the naked eye at the tip of this prefilmer. This can be clearly distinguished in Figure 4.16 where the bulk of the fluorescence signal is located.

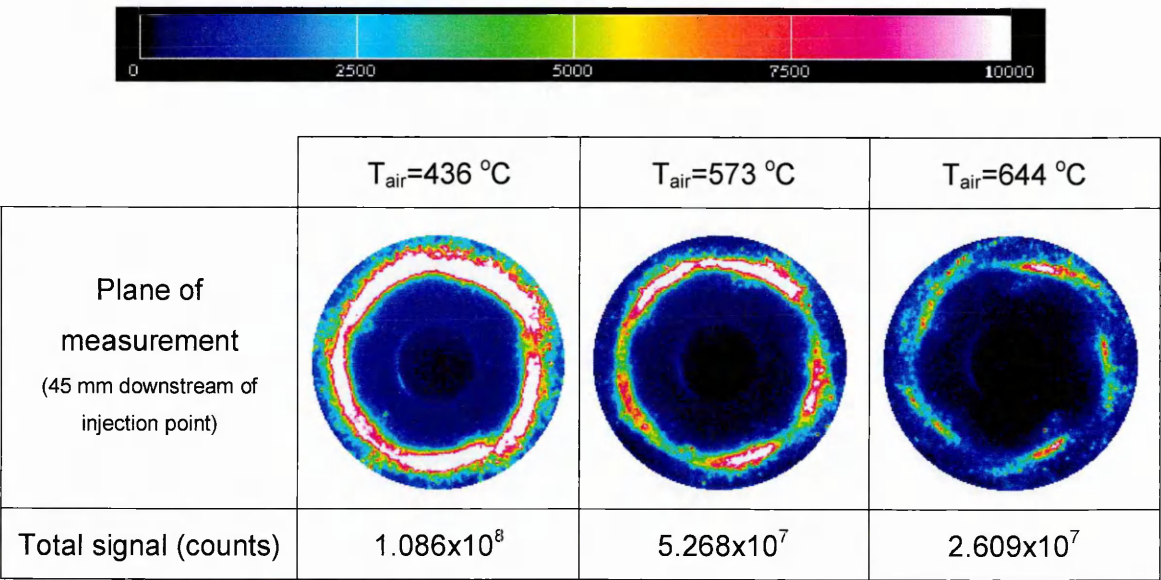


Figure 4.16 Fluorescence variation of azulene with temperature

The collected and summed signal of the region of the interest revealed to be very low compared with the expected values. Since liquid streaks could be observed, particularly at lower temperatures, a higher signal was anticipated. Based on the calibration curve, even if at the plane of measurements more than half of the fuel was

vaporised, the signal level should have been about 1.35×10^{11} counts. With increased temperature, the signal level was reduced as expected since azulene fluoresces strongly in the liquid phase.

Berlman (1971) studied the spectroscopic properties of azulene. He used a concentration of 0.23 g.l^{-1} of azulene dissolved in cyclohexane. He showed that the reduction of the fluorescence signal of azulene in the presence of oxygen was only 4%. Thus, azulene is weakly quenched in the presence of oxygen and can be assumed to be insensitive to quenching. Although in the present study azulene was dissolved in Exxsol, its fluorescence properties are assumed to be similar to the study of Berlman. Therefore, this experimental results suggest a very strong temperature dependence of the fluorescence of azulene. Unfortunately, primarily due to lack of time, it has been impossible to quantify the latter. This would require design of careful experiments which may be lengthy.

Consequently, wherever applicable the results of the liquid phase experiments would be presented under a qualitative form only. The main difficulties and further considerations of the calibration experiments are discussed next.

4.7.5 Further considerations

It has been shown that the fluorescence of the liquid phase (similar to the vapour phase) is a strong function of temperature. In order to quantify the effects of the temperature on the fluorescence signal, many considerations must be addressed. The main issues associated with the liquid phase quantification are thus briefly developed.

With the current calibration set up, the liquid jet is injected at right angle relative to the laser sheet. It is possible that as a result of multiple light scattering in the liquid column, in the immediate vicinity of the laser sheet, the fluorescence signal is overestimated. One possible way to overcome this would consist of injecting the jet at an angle, so that the cross sectional intersection with the laser sheet is an ellipse (rather than a circle). The part of the jet exiting the laser sheet thus will not be in the fluorescence path.

The measurement of the laser sheet thickness is also important in the overall accuracy of the calibration. In the present study this thickness is assumed to be constant. However, in reality this has to be determined over the height of the sheet. Attenuation of the laser light by the absorption of the dye is also another limiting parameter in the quantification of the results (Talley *et al.*, 1996).

Finally, the multi-component nature of the fuel is possibly the main constraint in quantitative liquid measurements. Exxsol and kerosene both are multi-component fuels and have fractions that evaporate faster than the others. Given this, the concentration of the fluorescent dye can change in such a way that the desired fluorescence properties are no longer fulfilled. Since the evaporation characteristics of exxsol were unknown a simple experiment was carried out. The solution of azulene was injected through a heated pipe. At temperatures of about 120-150 °C, the lighter fractions of exxsol started to evaporate. This was noticeable at the tip of the pipe where the liquid exited. However, the local wall temperatures of the pipe may have been slightly higher than that of the liquid fuel. This suggest that the onset of fuel evaporation will result in an increased dye concentration.

Therefore, further work needs to be done before an accurate fluorescence measurement takes this variation of the dye concentration into account (Melton, 1993 and McDonell & Samuelson, 2000). Nevertheless, despite the limitations and uncertainties in the calibration process, this method has potential for the study of sprays at room temperature. With the design of careful experiments a semi-quantitative measurement of the liquid phase may be possible.

4.8 Summary

Planar laser induced fluorescence (PLIF) has been chosen as a diagnostic tool for fuel-air mixture formation studies. A review of its applications to realistic combustion devices showed that quenching is the main factor limiting the extraction of quantitative data, in these applications. However, this is an aggravated problem at higher pressures and in a combusting environment. Based on this knowledge, a calibration method has been derived for studies limited to non-reacting environments at atmospheric pressure.

The vapour phase calibration consisted of the characterisation of the fluorescence signal as a function of temperature and fuel concentration. A vaporiser was designed to this end. This vaporiser was used to provide known conditions of AFR which could then be related to similar conditions in a realistic device. It was found that the fluorescence of naphthalene increased linearly with fuel concentration and temperature (over a limited range). The expected fluctuations in the temperature field of the LPP ducts, studied in this work, were anticipated to be small.

With regard to the study of the liquid phase, a preliminary investigation was carried out. It was shown that the careful selection of the tracer concentration, namely azulene, yielded a liquid fluorescence signal which was proportional to the volume and subsequently to the mass of the liquid. However, since limited time could be devoted to this calibration process, the effect of the temperature on the liquid fluorescence could not be quantified. In addition, other issues which were briefly discussed would make this calibration process very challenging. This was beyond the scope the present project and has been investigated only preliminary.

Chapter 5

LPP combustor module for small engines

5.1 Introduction

Small gas turbines such as helicopter engines and auxiliary power units are minor contributors to the overall emission of pollutants. They represent only a fraction of the total fuel consumption of gas turbines and thus constitute a minimal concern with respect to their impact on the environment. In addition, they operate at low altitudes and therefore have negligible impact on the depletion of the ozone due to NO_x emissions (Eatock & Sampath, 1993). Nevertheless, they are subject to regulations, though less stringent relative to large engines, and have been the object of developments aimed at reducing their emissions. The current study of a LPP combustor module presented here, is part of a European sponsored project, namely Brite-Euram Low NO_x. It is devoted to the evaluation of most promising NO_x reduction techniques. This project was carried out in association with Turboméca Ltd. (referred to as TM), the French helicopter engine and small gas turbine manufacturer. It is the third evolution (EV3) of a LPP combustor module which was developed during the early phase of this European project. It has shown satisfactory and promising emissions performance (Schott, 1998) and is the object of the present study for an improved characterisation of its operation. To this end, quantitative PLIF measurements of local equivalence ratios (representing mixing) were undertaken. Qualitative information on the liquid phase (vaporisation characteristics) was also gathered.

5.2 Description of TM EV3 configuration

Small gas turbine engines are often designed with centrifugal compressors and reverse-flow annular combustors (Steele, 1989). This combustor layout is attractive as the overall length of the engine can be reduced. This in turn, alleviates substantial problems concerning shaft dynamics and bearing design. However, this also results in

an arrangement where the combustor is located on a large mean radius exceeding the outer diameter of the turbine casing. Consequently, the flame-tube is large and requires cooling (Joos *et al.*, 1991). In addition, since the overall compressor ratios are lower for small engines, compressor exit temperatures are lower (Howell, 1993). This is important since complete vaporisation of the fuel is more difficult to achieve.

The combustor section of the test rig of the Turboméca LPP EV3 configuration is shown in figure 5.1. It simulates a reverse-flow combustor sector with dilution holes.

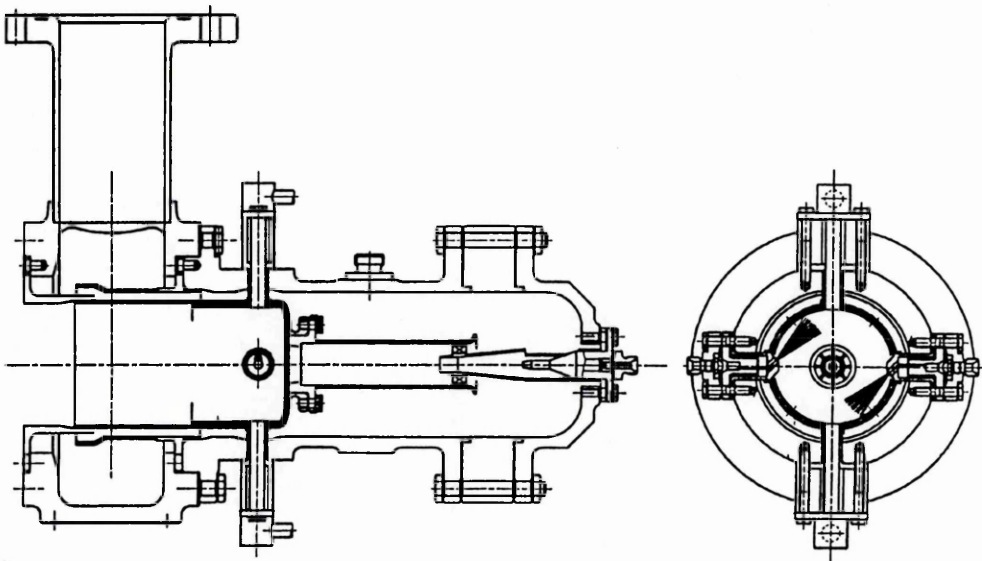


Figure 5.1 Turboméca LPP EV3 combustor test section

The fuel injection system is based on two pilot injectors and a main. The pilots are airblast injectors with angled fuel spray and can be seen on the right hand side of Figure 5.1. The main fuel injector is a simple airblast co-flowing plain jet injector. It is attached to a premixing tube where air surrounding the injector atomises the fuel. This is then connected to a prevaporising duct, of about 100 mm long (see also Figure 5.2). A swirler is used at the inlet of the duct to increase the turbulence levels and thus promote mixing. This swirler is also intended to entrain large droplets towards the prevaporising duct wall where additional vaporisation, along the duct wall, can be achieved. The end of the duct also incorporates a step, prior to the exit plane, as to

provide secondary atomisation of surviving droplets. This is particularly useful at part load conditions where low temperatures often result in incomplete vaporisation of the fuel (Schott, 1998). A heat shield is also incorporated at the exit of the prevaporising duct. It is used to create a larger recirculation area in the primary zone and to avoid flame quenching by the cooling air. This is aimed at limiting the emission of CO and UHC. However, in order to carry out non intrusive laser diagnostics optical access was necessary. Therefore, to minimise the cost of such hardware a simplified version of this rig had to be designed. Figure 5.2 shows the simplified rig which was designed around the main elements of the LPP module, namely the injector, the premixing and the prevaporising tube.

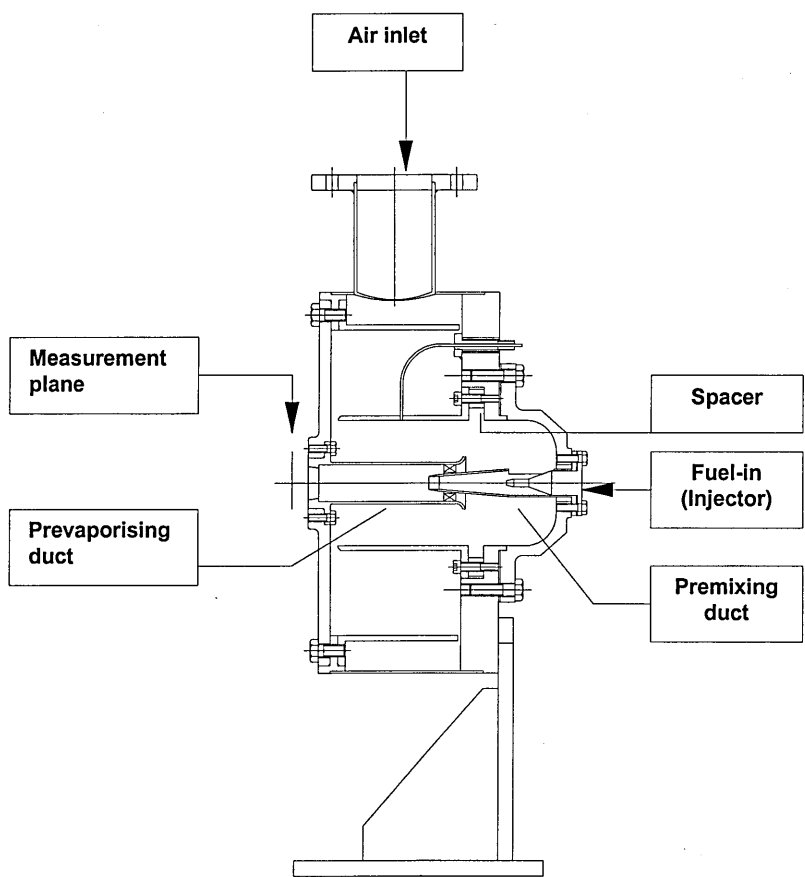


Figure 5.2 Experimental rig of TM EV3 combustor module

The reverse-flow nature of the combustor was preserved in this simplified configuration. The air which was supplied through a blower was heated by a 15 kW

electrical heater. To ensure an even air supply in the core region two drums were used. The gap between the wall and the second drum could be adjusted with a spacer as to obtain the desired operational pressure drop (4% in the present study). The measurements were carried out 3 mm downstream the exit of the LPP duct. The fuel was supplied through a pressurised tank and controlled by a calibrated floatmeter. A more detailed drawing of the general assembly can be found in Appendix 1.

5.3 Required vapour-phase measurements

In order to gain insight into the mixing characteristics of the LPP duct, a few conditions were to be investigated. The measurement of local equivalence ratios for the following cases were carried out. The overall inlet parameters of air and fuel mass flows are summarised in Table 5.1.

$T_{\text{air}} (^{\circ}\text{C})$	ϕ_{overall}	$M_{\text{air}} (\text{g.s}^{-1})$	Fuel flow (l.h^{-1})	Fuel flow (g.s^{-1})
333	0.60	10.31	1.876	0.418
	0.65	10.31	2.032	0.453
	0.70	10.31	2.188	0.488
377	0.60	9.88	1.796	0.400
	0.65	9.88	1.945	0.434
	0.70	9.88	2.095	0.467
450	0.60	9.42	1.712	0.381
	0.65	9.42	1.855	0.413
	0.70	9.42	1.998	0.445

Table 5.1 Vapour-phase experimental conditions

5.4 Vapour-phase calibration experiments

As discussed in chapter 4, determination of local equivalence ratios requires calibration of the fluorescence signal against known inlet conditions. Since the imaging set up was conserved between the calibration experiments and the LPP EV3 duct measurements, the calibration curve is that of Figure 4.12. The fuel for both the calibration and the experiments contain 4% naphthalene by mass in exxsol.

5.5 Image processing

A fully processed image was obtained from four separate images. Initially, the background signal was subtracted from the raw data images. This background image contained no fluorescence signal (no fuel) but accounted for scattering of the laser light in the measurement plane and the readout noise of the ICCD detector.

The variations in the laser sheet structure and intensity were corrected by a flatfielding image. This flatfielding was carried out in a UV grade cuvette (12.5 x 40 x 45 mm) which was filled with a homogeneous mixture of acetone vapour and air. The cuvette was placed in the measurement volume as to cover the exit plane of the duct. The background signal from the cuvette, containing no acetone was also removed from this flatfielding image. The laser sheet intensity variations, averaged over 100 laser shots, are shown in Figure 5.3.

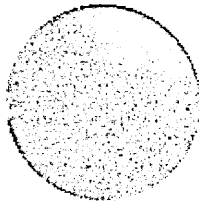


Figure 5.3 Flatfielding image

The final processed image (P) was thus a result of the following operations:

$$P = \left(\frac{R - B}{F - B_F} \right) \quad (5.1)$$

- R is the raw data image
- B is the background image
- F is the flatfielding image, correcting for laser sheet non-uniformities
- B_F is the flatfielding background image

The image processing software used for the above operations was a Unix based programme called CLIPS (Cranfield laser imaging processing software).

5.6 Vapour-phase results

The experimental set up for the measurements is identical to that of Figure 4.7. Equations 4.30 and 4.31 were used to determine local equivalence ratios. Figure 5.4 represents the results of the PLIF measurements for an inlet air temperature of 333 °C. The colour bar indicates absolute scale of local equivalence ratios.

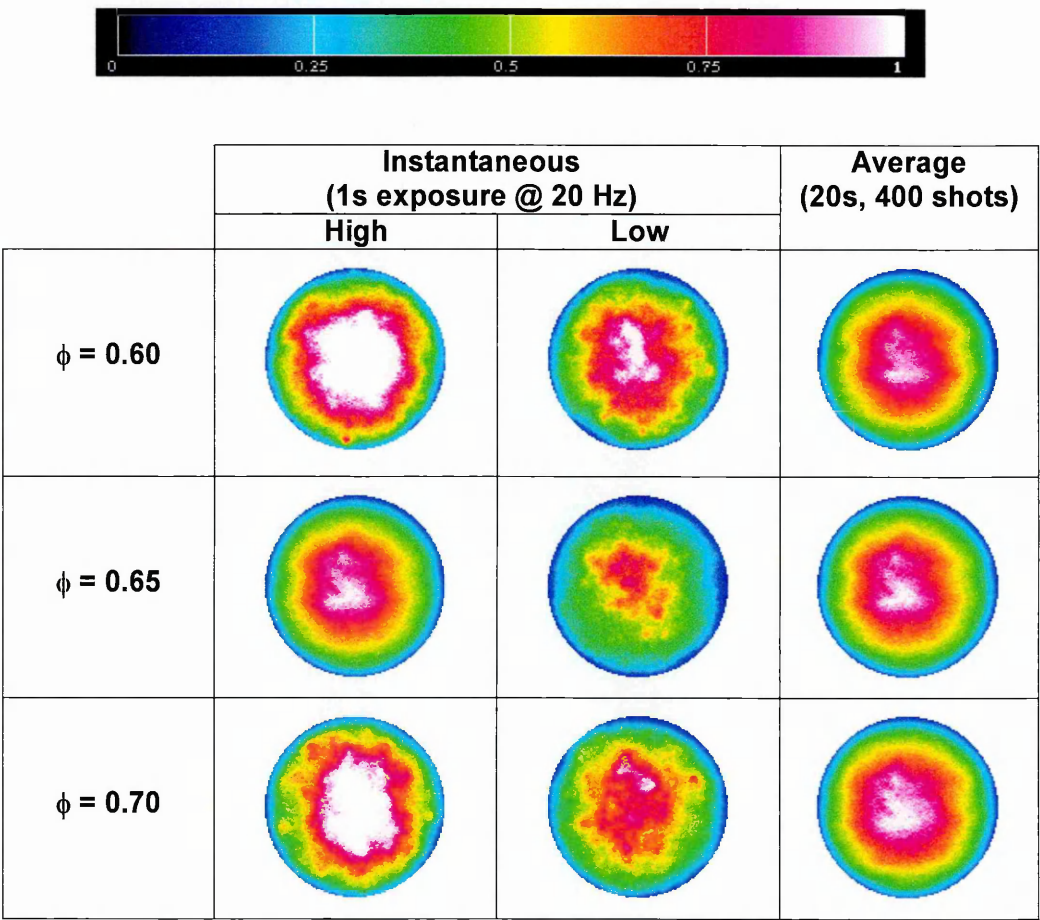


Figure 5.4 Local equivalence ratio for inlet air temperature $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$

The exit of the LPP duct has a diameter of about 22 mm. However, the above images cover a diameter of approximately 25 mm (112x112 pixels) centred on the exit of the duct. Given the swirling motion of the air flow and the fact that the measurements were carried out 3 mm downstream of the duct this was judged to be necessary. The high and low images represent frames of images with temporal variations in the fluorescence intensity.

Figure 5.5 shows the local equivalence ratios for inlet air temperatures of $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$. To avoid cumbersome data presentation the results of the measurements for $T_{\text{air}} = 377\text{ }^{\circ}\text{C}$ are attached in Appendix 2.

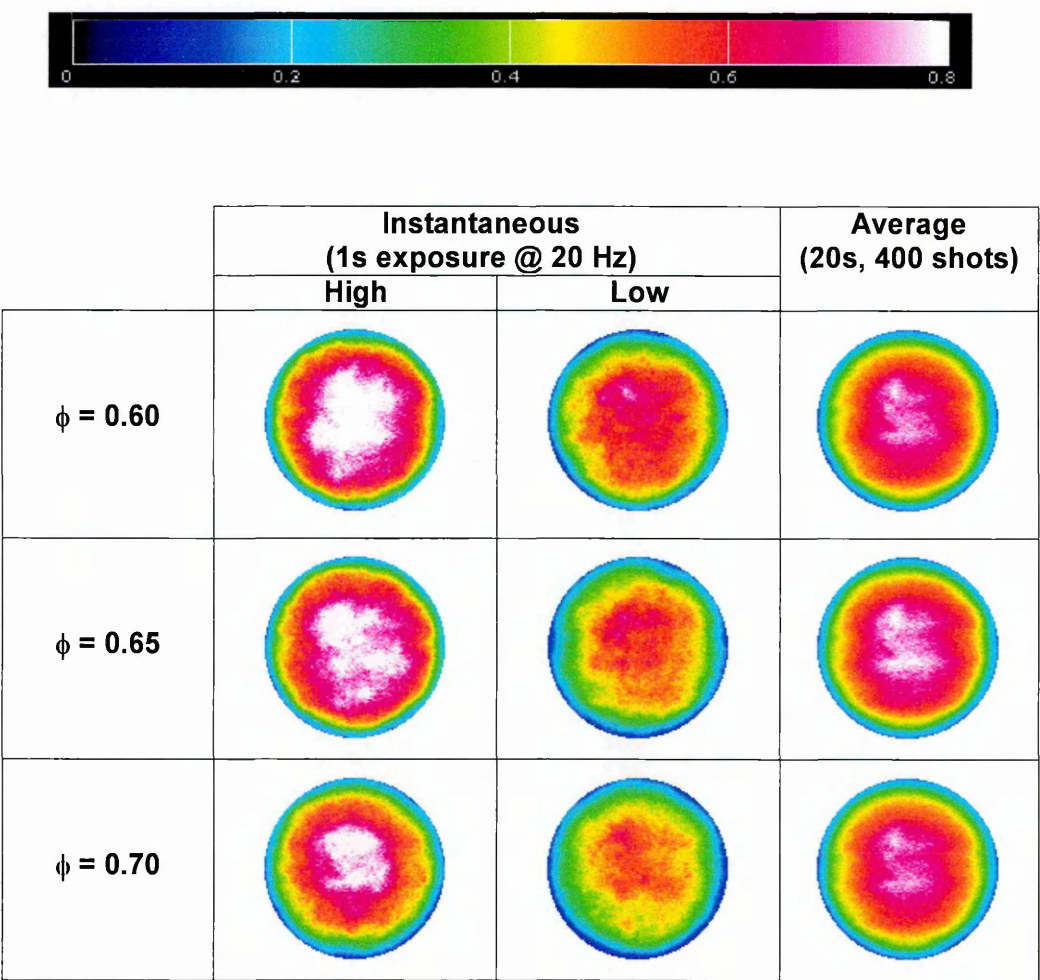


Figure 5.5 Local equivalence ratio for inlet air temperature $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$

The average local equivalence ratios along the horizontal centreline of the duct are plotted in Figure 5.6 to 5.8. The domain is intentionally limited to 22 mm diameter (100 pixels) which represents the duct exit diameter. Since air can be entrained at the duct exit it can potentially lower the temperature of the gas at the outer edges. This approach minimises gas mixture dilution by the surrounding air.

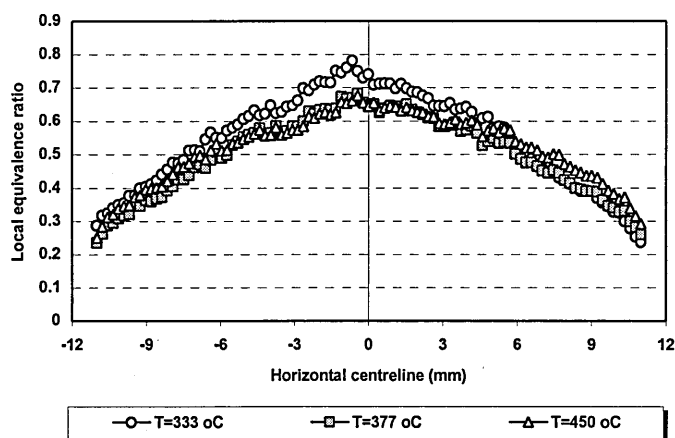


Figure 5.6 Local equivalence ratio along horizontal duct-exit centreline ($\phi_{\text{overall}} = 0.60$)

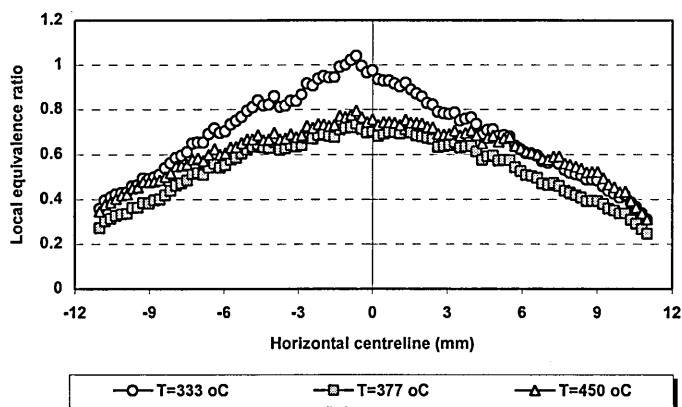


Figure 5.7 Local equivalence ratio along horizontal duct-exit centreline ($\phi_{\text{overall}} = 0.65$)

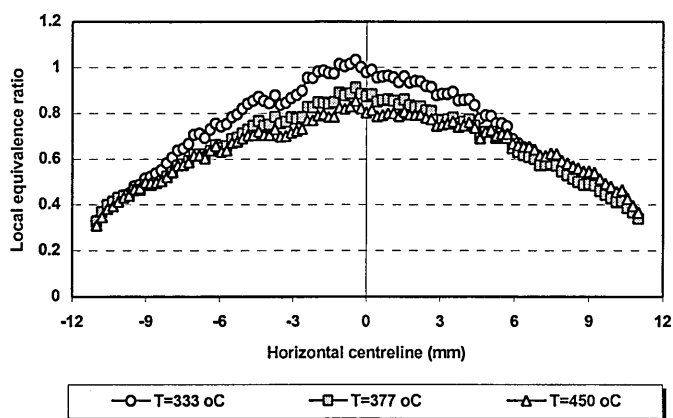


Figure 5.8 Local equivalence ratio along horizontal duct-exit centreline ($\phi_{\text{overall}} = 0.70$)

The examination of the images and the graphs of the local equivalence ratios revealed a few interesting features of this duct.

To start with, it could clearly be seen that the highest values of equivalence ratios were encountered in the central region of the duct. This was noticeable at all temperatures and fuel flow conditions. It suggests that the bulk of the vaporisation occurs in the core section of the duct.

Besides, the spatial distribution of the equivalence ratios showed a relatively large variation from the outer edges towards the centre of the duct. Ideally, in a LPP duct a homogeneous mixture is desired. This is intended to avoid regions with higher fuel concentrations and thus higher flame temperatures. With reference to the instantaneous images (high and low values), for a given point at the exit of the duct a variation of 20-40% in the local equivalence ratio could be observed. This may be attributed to the turbulence level in the premixing section of the duct with fluctuations in the fuel atomisation characteristics.

The maximum value of local equivalence ratio for the experimental conditions was found to be around $\phi \approx 1.0$. This is particularly relevant at low temperature of 333 °C. This may be due to the fact that at lower temperatures there is a small contribution of the liquid naphthalene fluorescence to the overall signal. As mentioned, the calibration is based upon the assumption that all the fuel is vaporised and that the contribution of the liquid signal is negligible. This is particularly evident in Figure 5.7 and 5.8 where the fuel flows are slightly higher.

For higher temperatures, $T_{\text{air}} = 377$ and $T_{\text{air}} = 450$ °C, the maximum values of equivalence ratios were around $\phi \approx 0.75$ and $\phi \approx 0.85$ respectively for an overall equivalence ratio of $\phi \approx 0.65$ and $\phi \approx 0.70$. Moreover, at those temperatures there is almost an overlap of the curves and similar values of equivalent ratios were measured. This trend in the spatial distribution of the fuel is also valid for the lower temperature of $T_{\text{air}} = 333$ °C but with a higher magnitude.

5.7 Error Analysis

As discussed in section 5.5 the processed images were obtained after arithmetic operations between four different images. The expected fractional error in measuring P (equation 5.1) is determined by:

$$\frac{\varepsilon_P}{P} = \sqrt{\left(\frac{\varepsilon_R}{R - B}\right)^2 + \left(\frac{\sigma_B}{R - B}\right)^2 + \left(\frac{\sigma_F}{F - B_F}\right)^2 + \left(\frac{\sigma_{BF}}{F - B_F}\right)^2} \tag{5.2}$$

- R is the mean raw data image intensity
- ε_R is the fluctuation intensity in the raw image
- B is the mean background intensity
- σ_B is the fluctuation in the background images
- F is the mean flatfielding image intensity
- σ_F is the fluctuation in the flatfielding image
- B_F is the average flatfielding background
- σ_{BF} is the fluctuation in the flatfielding background

The typical values of the above parameters for images presented in Figure 5.4 and 5.5 are summarised in Table 5.2.

Description	Symbol	Value (CCD counts)
Mean raw data image	R	3328
Mean intensity fluctuations	ε_R	240
Mean background intensity	B	80
Background fluctuations	σ_B	5
Mean flatfielding intensity	F	5364
Fluctuation in the flatfielding	σ_F	187
Mean flatfielding background	B_F	123
Flatfielding background fluctuation	σ_{BF}	15

Table 5.2 Analysis of the fractional error

With the above values, equation 5.2 yields an **expected fractional error of about 8.2%**. However, in practice other sources of error are also likely to contribute to this error. The main one is the variation in the temperature gradient and is discussed next.

5.8 Correction for temperature variations

The determination of the local fuel concentration, as explained in Chapter 4, is based on the knowledge of the temperature and the fluorescence signal intensity in the measurement volume. In processing the data it was thus necessary to assume a constant temperature in this region. Although, the inlet air temperature was known, it could not be used as a reliable parameter in the processing. Therefore, the maximum exit temperature of the fuel-air mixture was used for the latter. The mixture temperature was lower than that of the air as a result of fuel vaporisation. Alternatively, the processing could have been carried out using the mean temperature across the exit of the duct at a given experimental condition.

In addition given the current test configuration, for optical access, the exit of the duct was exposed to the air. Consequently, entrained air at room temperature could diffuse into the swirling jet at the exit of the duct. This would in turn lower the temperature in the outer edges of the flow field. As a result, the fuel concentration and the equivalence ratios would be underestimated.

In order to account for the variations in the temperature, measurements with a k-type thermocouple were carried out at the duct exit with an increment of 1 mm. Ideally, an instantaneous 2D temperature field is required for a pixel-by-pixel correction. This type of measurements can be achieved but were outside the scope and the allocated time for the present project. Therefore, no attempt was made to correct the local equivalence ratios due to temperature variations in images of Figure 5.4 and 5.5.

Nevertheless, these measurements showed that, in average, there was a reduction of about 10 °C in the mixture temperature when the overall equivalence ratio was increased from $\phi = 0.60$ to $\phi = 0.65$ (increased fuel flow). The mixture temperature decreased by a further 10 °C when the latter was increased from $\phi = 0.65$ to $\phi = 0.70$.

A detailed correction for all experimental conditions would be time consuming and tedious. However, two cases which were to be compared with CFD modelling results have been the object of a limited correction. This was carried out along the horizontal centreline of the duct (exit plane) only for an overall equivalence ratio of $\phi = 0.60$ and air temperatures of $T_{\text{air}} = 333 \text{ °C}$ and $T_{\text{air}} = 450 \text{ °C}$.

The temperature field at the exit of the duct, for the above cases, is shown in Figures 5.9 and 5.10.

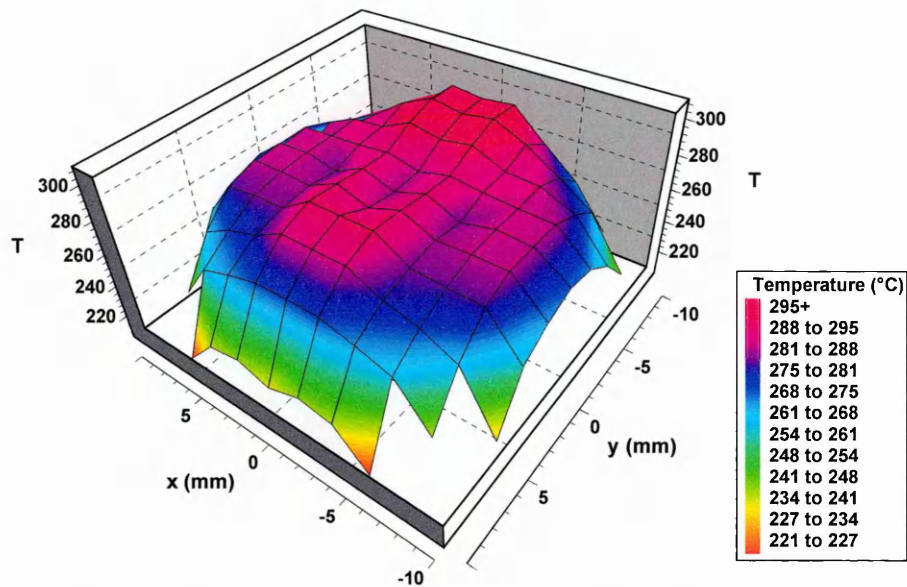


Figure 5.9 Temperature distribution at the exit of the duct
($T_{\text{air}} = 333\text{ }^{\circ}\text{C}$, $\phi = 0.60$)

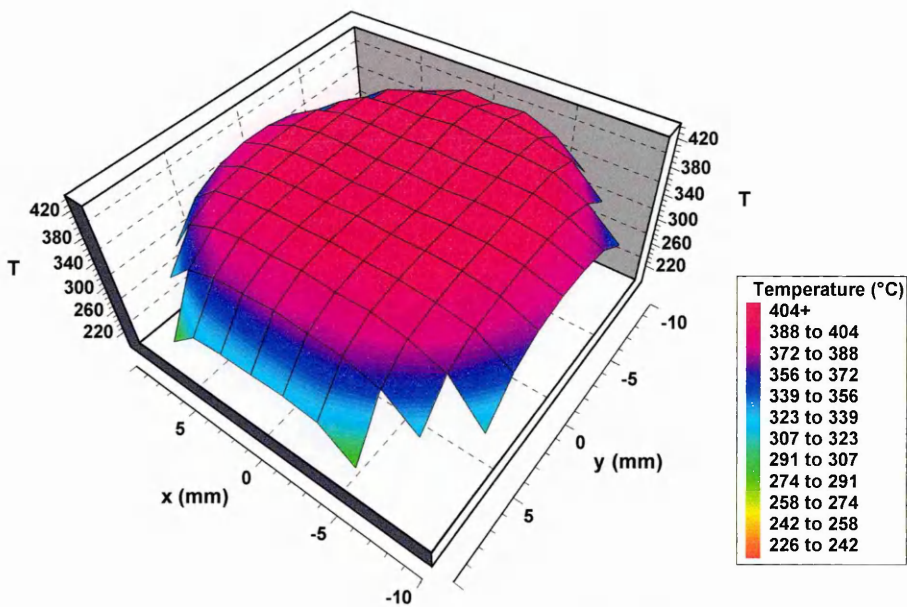


Figure 5.10 Temperature distribution at the exit of the duct
($T_{\text{air}} = 450\text{ }^{\circ}\text{C}$, $\phi = 0.60$)

It could clearly be seen that the temperatures at the outer edges of the flow field were lower as anticipated. Moreover, the temperature fluctuations in the central region of the duct-exit were higher for the case where $T_{air} = 333\text{ }^{\circ}\text{C}$. The temperature profile was more uniform at higher temperature of $T_{air} = 450\text{ }^{\circ}\text{C}$ since with improved vaporisation less liquid was likely to be present at the duct exit. The maximum mixture temperature for the former and the latter were respectively $300\text{ }^{\circ}\text{C}$ and $420\text{ }^{\circ}\text{C}$. The mixture temperature along the horizontal centreline of the duct ($y = 0$) is shown in Figure 5.11.

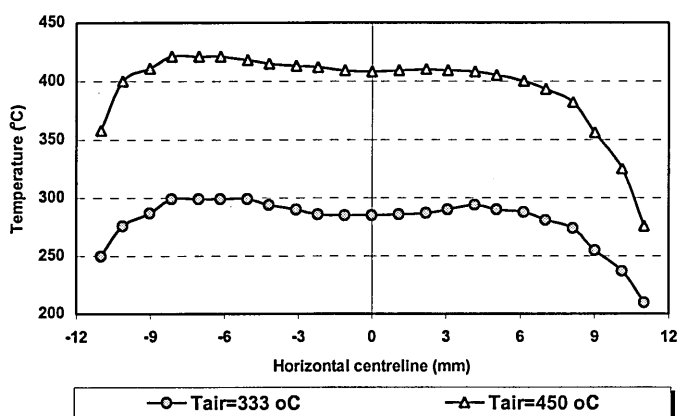


Figure 5.11 Duct-exit temperature along the horizontal centreline
($\phi = 0.60$)

Based on the above temperature profile it is possible to correct the values of local equivalence ratios for pixels corresponding to each measurement point. Alternatively, all pixel values can be corrected provided a linear interpolation is carried out between two successive measurement points.

This correction was achieved by adjusting the slope of the calibration curve which was used in order to determine the local fuel concentration (see calibration curves of Figure 4.12). By calculating the original value of the fuel concentration, through equations 4.30 and 4.31, a correction could be applied to the latter. For a given fluorescence intensity remains unchanged, the variations in temperature can be taken into account to yield a higher or lower fuel concentration depending upon the slope of the calibration line. This slope as shown was a linear function of the temperature. The results of the corrections are presented in Figure 5.12 and 5.13.

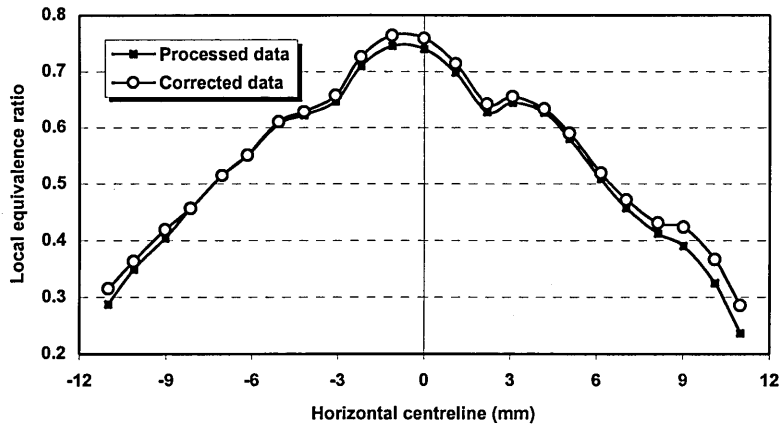


Figure 5.12 Corrected local equivalence ratio for selected points along the duct-exit horizontal centreline ($T_{\text{air}} = 333\text{ }^{\circ}\text{C}$, $\phi=0.60$)

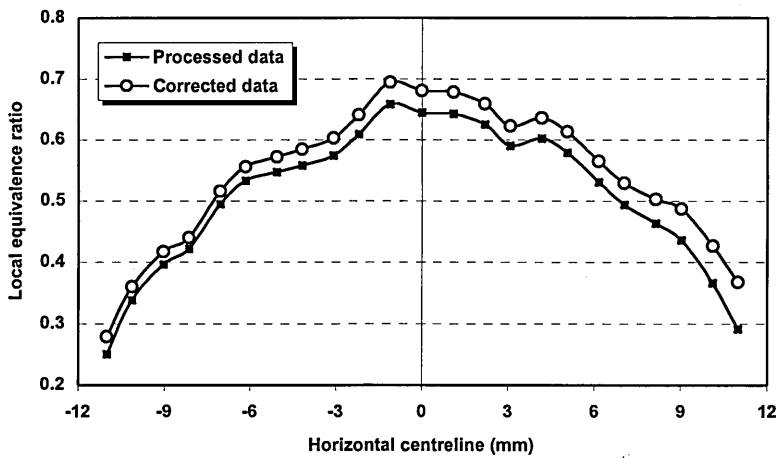


Figure 5.13 Corrected local equivalence ratio for selected points along the duct-exit horizontal centreline ($T_{\text{air}} = 450\text{ }^{\circ}\text{C}$, $\phi=0.60$)

For processing the data the mixture temperature was assumed to be uniform at the exit of the duct. This temperature was arbitrarily chosen as the maximum measured value in the exit plane of the duct. Consequently, the values of the fuel concentrations and the equivalence ratios were underestimated. The maximum mixture temperature for an air inlet temperature of $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$ and $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$ were respectively $300\text{ }^{\circ}\text{C}$ and $420\text{ }^{\circ}\text{C}$. The detailed correction procedure for the above cases can be found in Appendix 3 and 4.

Prior to correction, the average equivalence ratio along the horizontal centreline of the duct at $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$ and $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$ were $\phi = 0.55$ and $\phi = 0.53$ respectively (for an inlet overall equivalence ratio of $\phi = 0.60$). As a result of the correction, they were in both cases $\phi \approx 0.57$. This slight discrepancy relative to a value of $\phi = 0.60$ can be attributed to non-homogeneity of the mixture and the deliberate limitation of the study domain to the duct exit diameter (22 mm). Since the measurements were carried out 3 mm downstream the duct exit the actual flow cross section would cover an area with a larger diameter. Important temperature drop and fluctuations were encountered at the edges of the flow and thus to minimise errors, the calculations were limited to a domain where the temperature readings were stable.

On average, a temperature variation of $100\text{ }^{\circ}\text{C}$ resulted in about 15% error in the value of the equivalence ratio. However, the typical temperature variations in the core of the flow were much smaller (around $20\text{--}30\text{ }^{\circ}\text{C}$). The subsequent errors are essentially about 3-5%. The result of the vapour phase measurements in Figure 5.4 and 5.5 are thus slightly underestimated, depending upon the actual temperature compared with the measured maximum temperature.

5.9 Liquid-phase results

The liquid-phase measurements were carried out using 0.0352% azulene by mass in exxsol. Since the fluorescence of azulene is much stronger in the liquid phase, lower temperature investigations were particularly attractive.

The investigation of the vapour-phase, using naphthalene (Section 5.6) was limited to the upper range of operating temperatures. Therefore, in the vapour-phase, low temperatures could be an important source of error since interference from the liquid naphthalene could result in an overestimated fluorescence signal.

The measurements were made for various air temperatures and overall equivalence ratios of $\phi = 0.60$, $\phi = 0.65$ and $\phi = 0.70$. The investigated air temperatures for the liquid

phase were, $T_{\text{air}} = 219\text{ }^{\circ}\text{C}$, 258, 283, 303, 333, 377 and $450\text{ }^{\circ}\text{C}$. However, to avoid cumbersome data presentation only two cases were included here. Figure 5.14 and 5.15 show the processed fluorescence signal for the experimental cases of $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$ and $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$. The results are presented under a qualitative form.

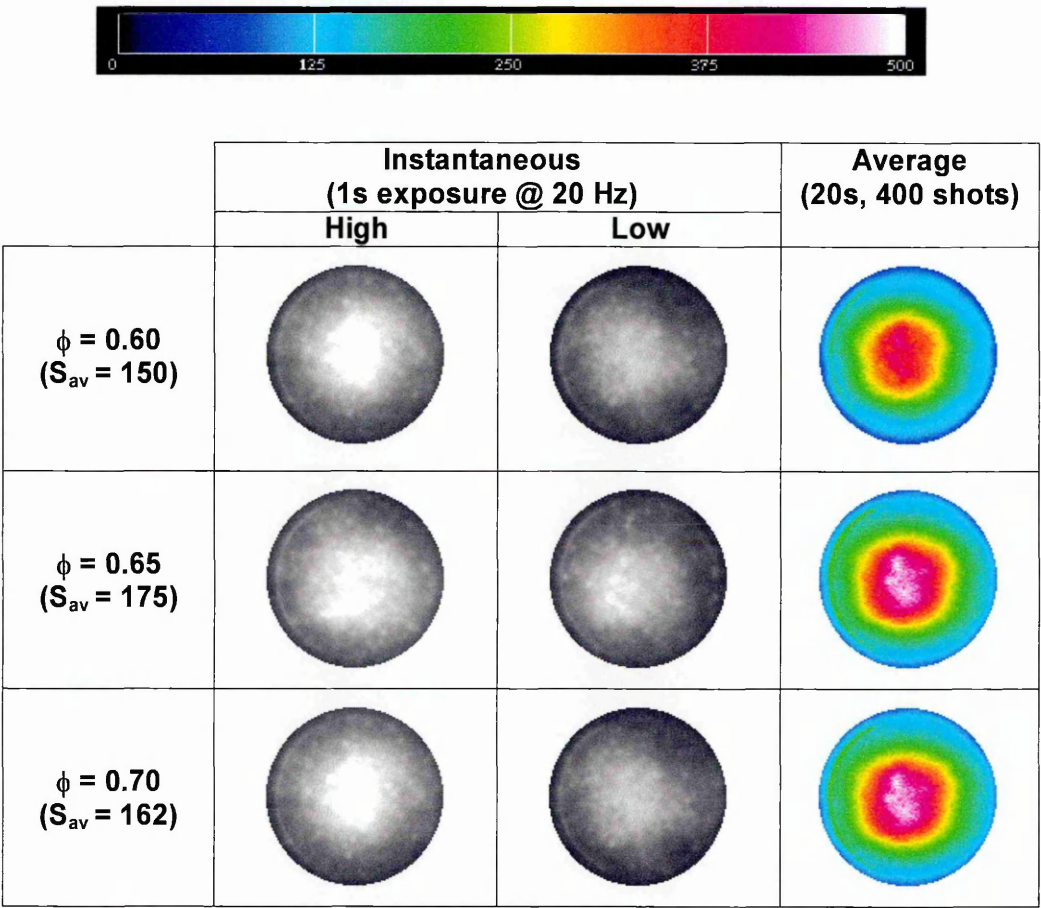


Figure 5.14 Fluorescence of azulene at $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$.

The mean fluorescence signal across the duct exit was calculated for the time averaged image (400 laser shots) and can be see in the left hand column. For an air temperature of $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$ the former is about 160 counts and changes very slightly with increased equivalence ratio. The highest intensities were located at the centre of the duct where the presence of the liquid was the highest. For convenience, the instantaneous images were shown on a black and white false scale. They represent an accumulation of 20 laser shots.

The fluorescence of azulene at higher air inlet temperature of $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$ is shown in Figure 5.15. The mean fluorescence intensity for the time-averaged images were lower. Since the air temperature was higher, a higher fraction of the fuel was evaporated. This in turn, resulted in a reduced concentration of liquid azulene, with subsequently lower overall signal intensity. At this temperature the mean signal was about half of the case where the air temperature was $T_{\text{air}} = 333\text{ }^{\circ}\text{C}$ (80 counts as opposed to 160 counts).

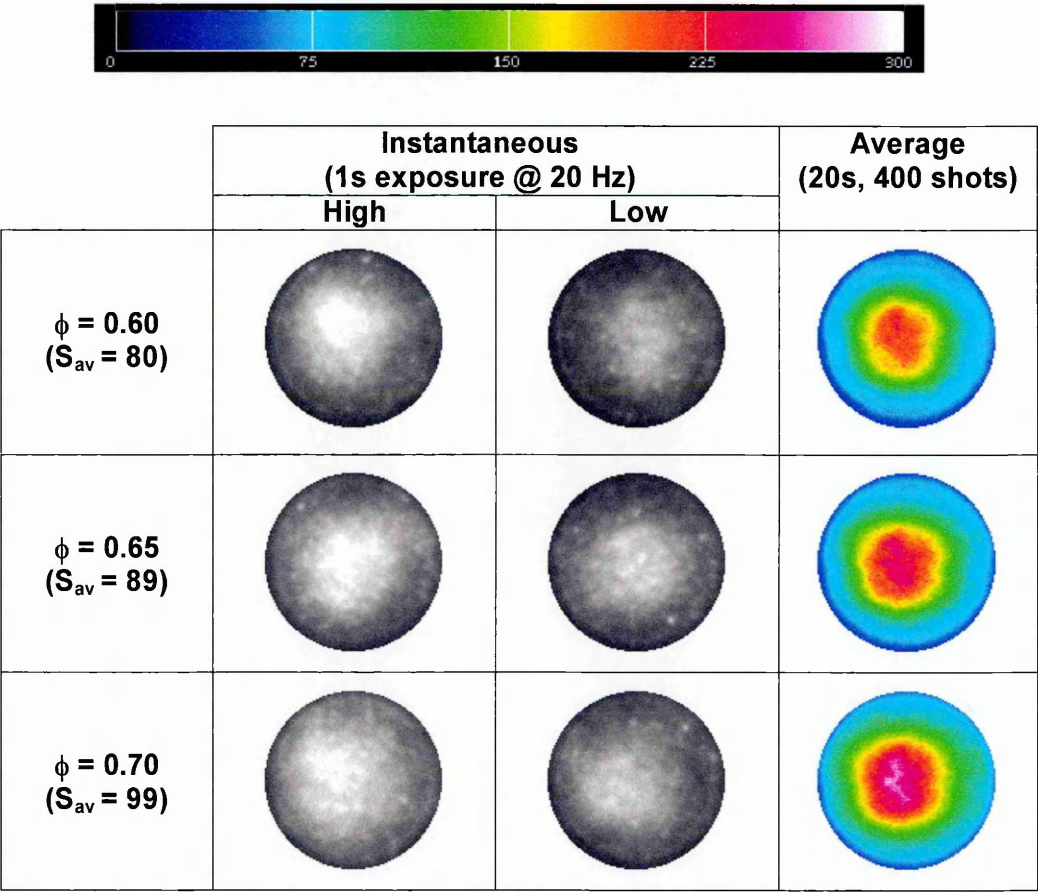


Figure 5.15 Fluorescence of azulene at $T_{\text{air}} = 450\text{ }^{\circ}\text{C}$.

The mean signal intensities were again similar for the different overall equivalence ratios. Therefore, it was decided to assess the variation of this signal over the entire range of air temperatures only for an overall equivalence ratio of $\phi=0.60$. In addition, this assessment was only applied to the horizontal centreline of the duct exit since the fluorescence signal was reasonably symmetrical relative to the x and y axis. The results are shown in Figure 5.16.

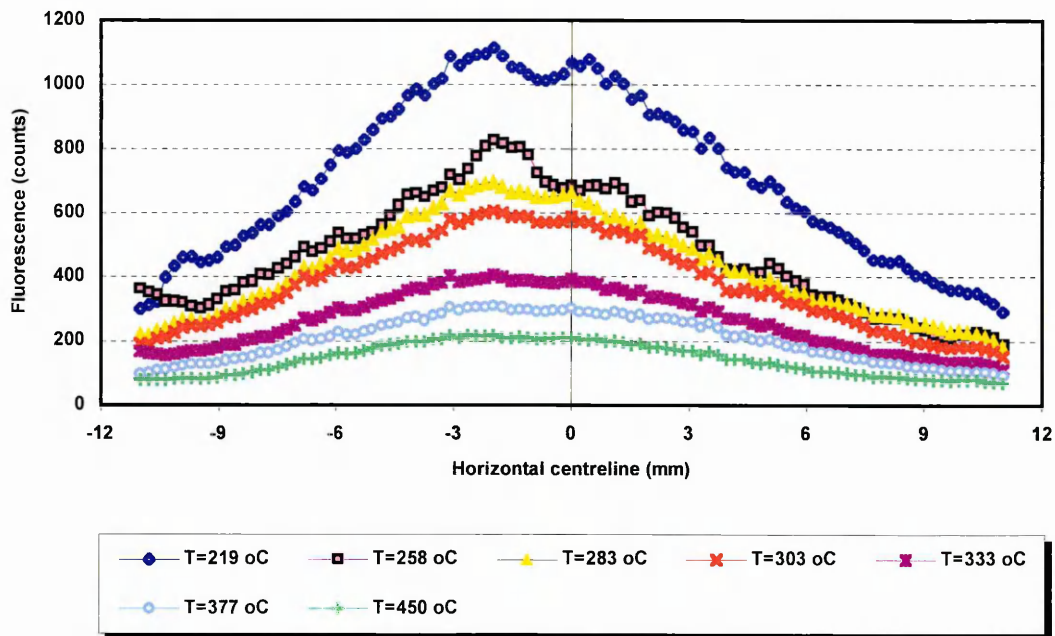


Figure 5.16 Fluorescence signal variation along the duct-exit horizontal centreline
(T is the air temperature, $\phi = 0.60$)

It could clearly be seen that at lower air temperatures the signal was stronger for a given position along the centreline. Nevertheless, near the outer edges of the duct the signal intensities were observed to be within a close range. The highest signal intensities were observed at the centre of the duct and smaller variations were recorded in this region with increased air temperature.

Moreover, the increased air temperature resulted in a flatter signal distribution, evidence of higher degree of fuel vaporisation. For instance, variations in the signal intensity for the region $[-3, 3]$ mm were negligible at $T_{\text{air}} = 450$ °C whereas these variations were about 20% at $T_{\text{air}} = 219$ °C. For a fully vaporised case the signal should be a flat curve with a very low signal intensity.

The mean fluorescence signal intensity of the time-averaged images were determined for all experimental conditions at the above equivalence ratio ($\phi=0.60$). The former was plotted against the air temperature and the results are shown in Figure 5.17.

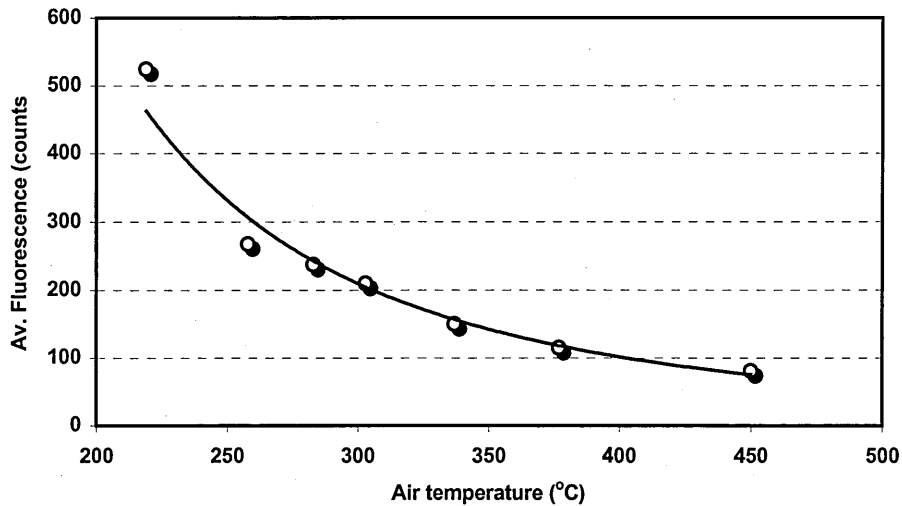


Figure 5.17 Variation of average azulene fluorescence with temperature across the duct exit ($\phi=0.60$)

A sharp reduction in the average fluorescence intensities was observed with increased air temperature. Given that azulene has a boiling point of 242 °C and if it is assumed that at 219 °C the fuel has not undergone any vaporisation, a qualitative evaporated fuel fraction can be calculated. However, in practice the lighter fractions of the fuel would have started to evaporate. Nevertheless, azulene is expected to be primarily in its liquid state at that temperature (219 °C). The onset of azulene vaporisation could be noticed at air temperature of 258 °C where an increase of 40 °C in the air temperature resulted in half the average fluorescence signal (Figure 5.17).

Based on this arbitrary datum point of 219 °C where all the fuel was assumed to be liquid, the ratio of the fluorescence signals should provide a comparison on the relative vaporisation of the fuel. It was further assumed that the fluorescence properties of azulene were similar over the entire temperature range so that this comparison could be made.

Although uncertainties were associated with this approach, it could provide useful insight into the evaporation characteristics of the duct as a function of air temperature. The results are shown in figure 5.18 for successive air temperatures of 258, 283, 303, 333, 377 and 450 °C (at 219 °C the evaporated fuel fraction was assumed to be 0%).

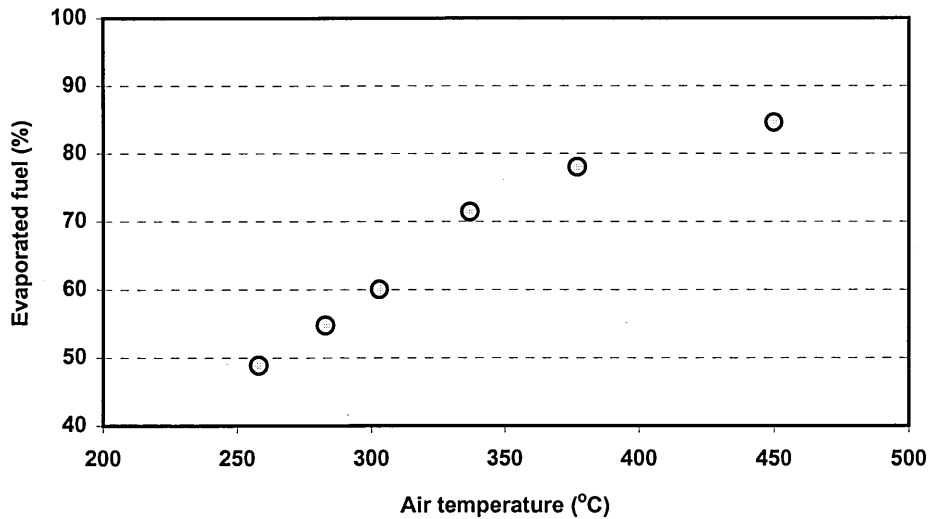


Figure 5.18 Relative evaporated fuel percentage as a function of air temperature (relative to 100% liquid fuel at 219 °C, $\phi=0.60$)

As an indication, half of the fuel was thus expected to be vaporised with an air temperature of 260 °C. An increase of about 200 °C in the air temperature resulted in an increased vaporisation by about 35%. At 333 °C and 450 °C the evaporated fuel fractions were about 72 and 85% respectively.

5.10 Droplet dispersion

The droplet dispersion in the small engine LPP duct was modelled at Turboméca Ltd. and was provided by Bissières (2000). The influence of the turbulence on the dispersion of the droplets was simulated for the condition where $T_{\text{air}} = 333$ °C. The tracking of the droplets was achieved using a Lagrangian formulation and frame of reference. The droplets were injected at two different locations, namely on the axis of the duct and at the lip of the premixing tube. The SMD for this computational case was estimated to be 36.5 μm . The injection locations can be seen in Figure 5.19 where the range of the injected diameters is indicated by the colour scale. The lip of the premixing tube is downstream of the swirler which is attached to it. The assembly of the premixing tube, the swirler and the vaporisation duct can be seen in Figure 5.2.

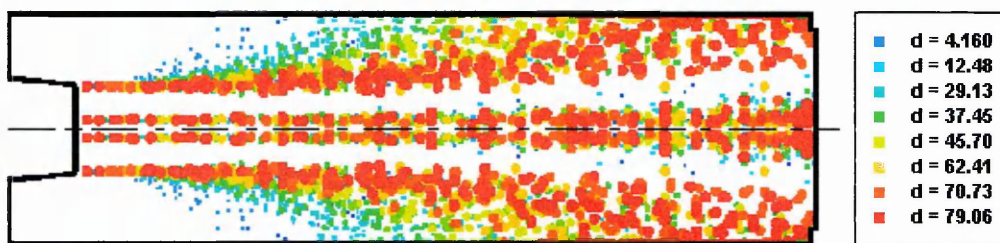


Figure 5.19 Droplet trajectory as a function of injection diameter (d in μm)

The droplets which were injected on the axis of the duct followed by and large the same trajectory and remained very close to the axis over the entire range of injection diameter. On the other hand, the droplets injected at the lip of the premixing duct showed a different dispersion pattern. The smaller diameters were entrained faster towards the wall of the duct, due to the swirl, whereas large diameters with higher momentum were shown to make contact with the wall further downstream. As discussed previously both the experiments and the computational results agreed on the presence of the liquid near the centre of the duct. Given the above droplet dispersion characteristic it can be inferred that, in practice, the bulk of the atomised fuel was located around the axis of the duct. A relatively small amount of the fuel reached the outer lip of the premixing duct.

5.11 Summary

PLIF measurements of both the vapour-phase and the liquid-phase were carried out on the TM LPP combustor module for a small gas turbine engine. Quantitative measurements of the local equivalence ratios at the exit of this LPP duct provided an insight into its mixing performance. A linear correction for the temperature field fluctuations was also applied to two experimental cases. The corrected overall equivalence ratios along the centreline of the duct revealed excellent agreement with the inlet overall equivalence ratio. The spatial distribution of the fuel concentration, showed higher values of equivalence ratios at the centre of the duct. Thus, although the overall equivalence ratio is lean, the centre of the duct is relatively fuel rich relative to its periphery.

The qualitative assessment of the liquid fuel placement in the duct showed that there was an important reduction in the fluorescence signal with increased air temperature. Based on the assumption that the onset of fuel vaporisation would occur at an air temperature of 219 °C an estimate of relative fuel evaporation as a function of air temperature was suggested. In reality the evaporation rate is believed to be underestimated since the lighter fractions of the fuel are expected to evaporate above 120-150 °C.

In addition, the vapour and liquid phase peak fluorescence intensities were located at the centre region of the duct. This suggests that the liquid was placed in the centre of the duct and that the bulk of the vaporisation occurred in this region. As an indication, with reference to Figures 5.6 to 5.8, the contribution of the outer edges of the duct (radius 7.5 to 11 mm) to the overall vapour phase signal was calculated. It was found that on average about 23-25% of the vapour was located in this region. The contribution of the liquid phase signal intensity, for all temperatures, in the same region was on average about 9.5-10.5% relative to the overall fluorescence signal (Figure 5.16).

Given the above observations and the result of the droplet tracking it could be concluded that a higher fraction of the atomised liquid could be directed towards the wall of the premixing tube and the vaporisation duct. In the current configuration the bulk of the liquid was observed around the centre of the duct (10% in the periphery between radius 7.5 to 11 mm). Therefore, by modifying slightly the plain jet airblast atomiser, it should be possible to obtain a wider spray cone angle. This in turn should result in better evaporation through effective use of the duct wall and the step at its exit. Alternatively, this can be achieved by integrating a swirler upstream of the injector to promote radial dispersion of the atomised fuel in the premixing section first and then in the prevaporising duct.

Consequently, an increased equivalence ratios at the periphery of the duct could be achieved. The resulting mixture would be more homogeneous with an overall leaner spatial fuel distribution since it would tend to lower the equivalence ratio values at the centre of the duct and increase those of the outer edges. This is anticipated to enhance the emission performance of the LPP module.

Chapter 6

LPP combustor module for large engines

6.1 Introduction

Large gas turbines encompass primarily the civil aviation engines but also industrial gas turbines for power generation. Since civil transport aircraft operate in altitudes where the ozone concentration is the highest, their emissions have been subject to much more stringent regulations than that of the small gas turbines. In addition, with the projected growth of the subsonic passenger traffic there is a need to minimise the emission impact of those aircraft on the environment. As previously discussed, the LPP combustion concept is the most promising technique to such an end. The LPP module, presented in this chapter, was schematically designed by Rolls-Royce plc. (referred to as RR) during the early phase of the European project Brite-Euram Low NO_x. At present, there is a need to develop a better understanding of the LPP modules prior to a successful application in an operating engine. To this end, a detailed design of an optical LPP module was carried out. The objectives of this project were to study and characterise the mixture preparation in this novel LPP premixer featuring a conical centre-body. Qualitative PLIF was used to achieve this characterisation. The experimental results of various geometries and operating conditions are discussed in this chapter. Evidence of the flame position and structure was also gathered by high speed video recording. A CD-ROM containing video clips of various tested geometries is provided at the end of this thesis.

6.2 Description of RR LPP module and its configurations

In the following sections a description of the LPP module and its features is presented. The typical operating conditions, the various tested configurations and plane of measurements are also detailed. Finally a short description of the atmospheric test rig to which the LPP module was integrated is provided.

6.2.1 Features of the RR LPP duct

The LPP module can be essentially divided into six main components, namely the swirlers, the centre-body, the injector, the prefilmer, the duct and the dump combustor section. A drawing of the LPP module is shown in Figure 6.1.

The swirlers are all radial type swirlers. Compared to axial swirlers they are attractive because they are easier to manufacture and can be more easily modified to alter the air flow characteristics (Halpin, 1993). For instance their diameter and thickness can be reduced with simple machining operations. The premixer incorporates four radial swirlers, three of which are used with the main air flow and a smaller one is combined with the centre-body. A series of swirlers with nominal swirl angles of 30, 45 and 60 degrees were designed. The 30 and 45 degree swirlers have both 36 vanes and the 60 degree swirler has 30 vanes. The centre-body swirler due to its smaller diameter has 24 vanes. They can be used either in a co-rotating or counter-rotating arrangement.

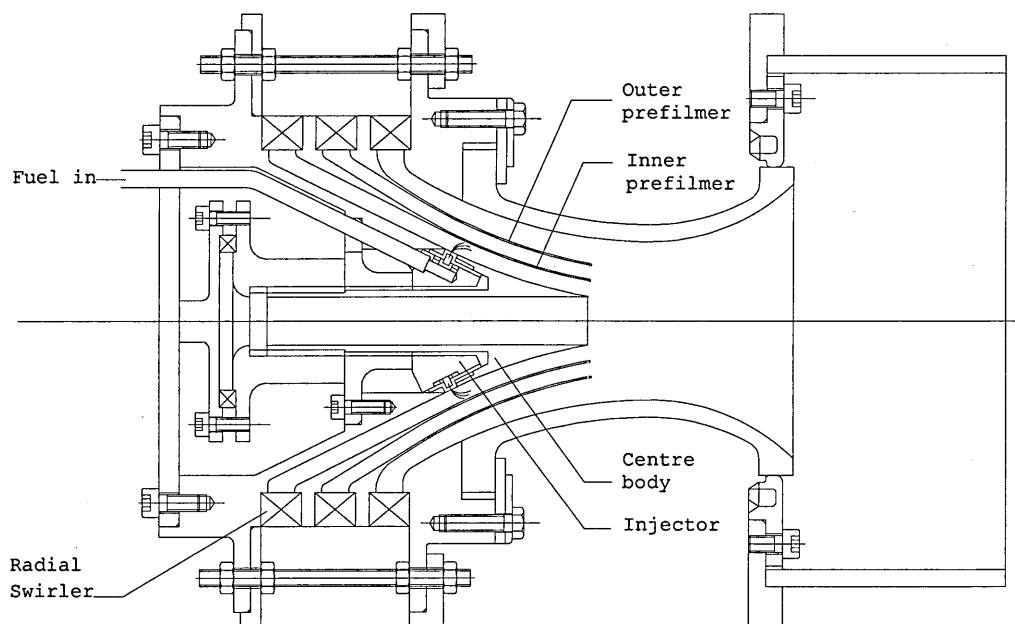


Figure 6.1 A view of RR LPP combustor module

The centre-body is of a conical shape to which the fuel injector is attached. In order to obtain a spray with small variations in the circumferential fuel distributions it was decided to laser drill the injector holes (15 holes with diameter 0.35 mm). After drilling, the two

parts of the injector were electron beam welded together and finally the fuel inlet pipe vacuum brazed to it. These operations were necessary as to minimise the distortion of the injector holes which can occur under conventional welding, due to large heat fluxes involved. The accuracy of the laser drilling was assessed in a patterning experiment.

The liquid from each injection hole was collected over a long period of time to minimise errors and weighed with a sensitive scale. The deviation of each hole relative to the average collected weight of liquid is shown in Figure 6.2. Although a variation of $\pm 3\%$ is accepted as the norm with conventional drilling, the result of the laser drilling was somewhat disappointing since large variations were observed for a few of the holes.

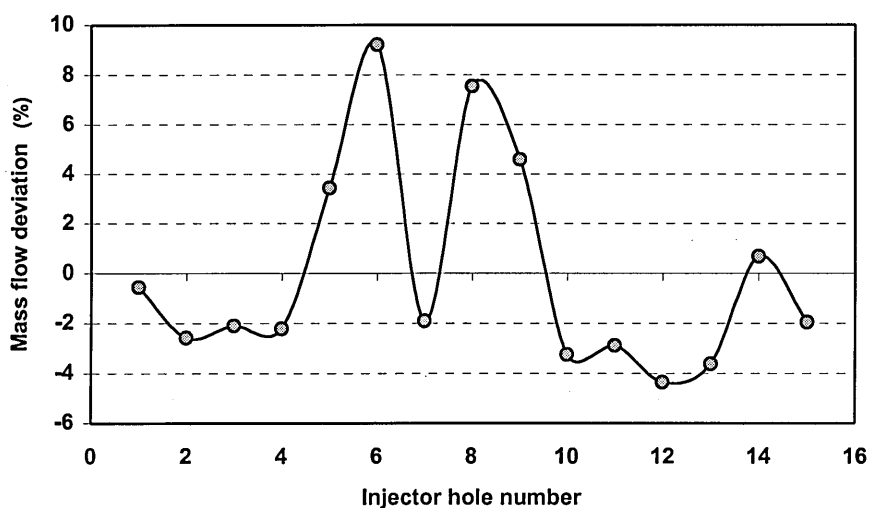


Figure 6.2 Injector patterning (deviation relative to the mean)

Two long fuel prefilms were also used. The prefilmer close to the injection point and the injection channel will be referred to as the inner prefilmer and the other as the outer one (Figure 6.1). They can be reduced in length as to provide further penetration of the fuel jets in the airflow. The premixing duct was made of a convergent-divergent section with curved walls. The purpose of the convergent section is to provide a constant flow acceleration as to avoid flashback. In the divergent section the flow decelerates prior to entering the section called the flame tube. This flame tube, in effect, is a simple dump combustor which constitutes the primary zone of combustion.

6.2.2 Typical operating conditions

The advanced gas turbines for large engines operate at high compressor pressure ratios and temperatures. The typical values for such an engine are detailed in Table 6.1 and were provided by Rolls-Royce plc.

Condition	Thrust (%)	T_{in} (°C)	P (kPa)
Take-off	100	644	4760
Cruise	44	573	1758
Approach	30	436	1871

Table 6.1 Typical operating conditions of an advanced aero-engine gas turbine

For the experiments, the above three temperatures were chosen to cover a wide range of operating conditions. However, the tests could only be carried out at atmospheric pressure. The operating pressure drop across the combustor was 4%. Typical operating conditions of the present LPP module were in the range of 60.4 to 66.40 g.s⁻¹ of air and fuel mass flows of 1.84 to 2.41 g.s⁻¹ for the three above temperatures.

6.2.3 Tested geometries and measurement planes

The optical fused silica duct was essential in order to undertake non-intrusive laser fluorescence imaging of the spatial fuel distribution. Therefore, the outmost care must have been taken to avoid possible damage due to problems such as vibrations, thermal stresses and acoustic pressure oscillations. In a preliminary and cautious assesment of the premixer, with a metallic duct, it was found that the quietest operation was achieved with the following combination of the swirlers: 45, 60 and 30 degrees respectively for the inner, middle and the outer channel. The centre-boody swirler was employed in a counter rotating configuration of -30 degrees (see Figure 6.3).

The sign convention for the swirler angles is as follows: a positive swirl angle indicates that the flow is rotating clockwise about the axis of the premixer and that a negative swirl angle is for anticlockwise rotation of the flow about this axis. This swirler arrangement was kept constant throughout all the experiments. It was anticipated that the flame would be stabilised near the exit of the premixing duct. Consequently, given the nature of the calibration and the assumption of isothermal flow the measurment

planes were kept well within the premixing duct as to avoid possible interference with the flame. The positions of the measurement planes are indicated relative to the end of the centre-body exit. The projected distance on the axis of the premixer, between the injection point and the centre-body exit, is about 40 mm. In addition, plane 2 corresponds to the throat of the duct which has a diameter of 46 mm.

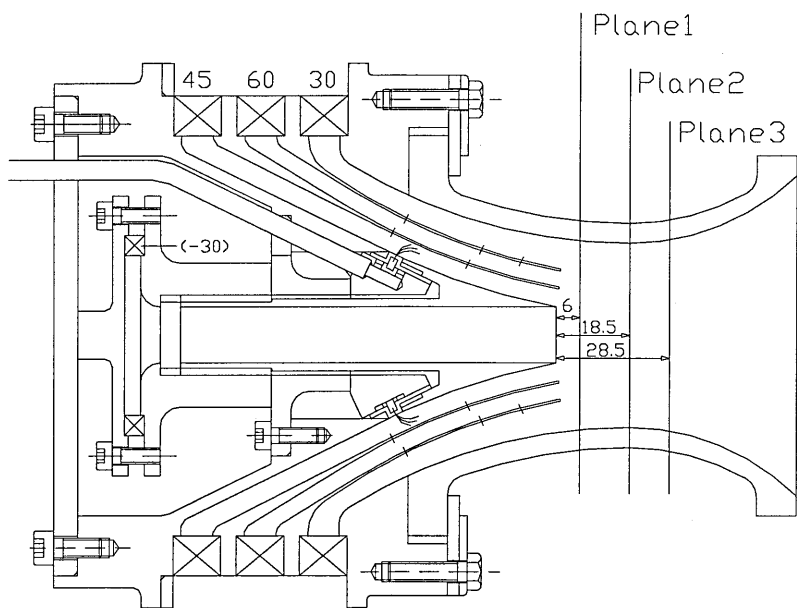


Figure 6.3 Details of experimental testing conditions

With regard to the tested geometries the dashed lines on the prefilms of Figure 6.3 indicate the trimming diameter of the inner and outer prefilms. This trimming was a mean of assessing the characteristics of the duct at different fuel jet penetrations and subsequent dispersion.

Build	Injector	Inner prefilmer	Outer prefilmer
Geometry 1	15 holes	long	long
Geometry 2	15 holes	cut by 23 mm	long
Geometry 3	15 holes	cut by 42 mm	long
Geometry 4	15 holes	cut by 42 mm	cut by 20 mm
Geometry 5	15 holes	cut by 42 mm	cut by 39 mm
Geometry 6	5 holes	cut by 42 mm	cut by 10 mm
Geometry 7	5 holes	cut by 42 mm	cut by 39 mm

Table 6.2 Configuration of the main tested geometries

The summary of the main investigated geometries are listed above, in Table 6.2.

6.2.4 LPP module test rig

The LPP module was integrated into a test rig in which the air flow was supplied through a blower. The air mass flow was determined by measuring the pressure drop across a bell-mouth nozzle at the inlet of this blower. Besides, a pre-heater upstream of the LPP module was employed to heat the air. The pre-heater consisted of a small can combustor burning propane and was an economical way of heating the air, up to temperatures of 1100 K.

Since oxygen was depleted during the preheating combustion, pure oxygen had to be added to the air flow so that the air contained 21% mole fraction of oxygen prior to combustion in the LPP module. The fuel to the LPP module was supplied through a pressurised tank. The flow was controlled with a Platon control valve and measured with a calibrated turbine flowmeter. The fuel air mixture was finally ignited downstream of the dump combustor sector using a Lodge high energy spark plug.

A more detailed description of the performance characteristics of the LPP rig has been investigated by Harding (1996). The details of the general assembly of the LPP combustor module and a section of the test rig can be seen in Appendix 5.

6.3 Experimental set-up for fuel visualisation

6.3.1 LPP rig and imaging set-up

A schematic of the experimental set-up for planar LIF fuel concentration measurements is shown in Figure 6.4. The rectangular beam from the Excimer laser was formed into a sheet through a spherical and two cylindrical lenses. By adjusting slightly the angle of the reflective mirror, the laser sheet could be directed towards each plane of measurement. A micrometer was used to ensure that the mirror was returned to its initial position for each plane.

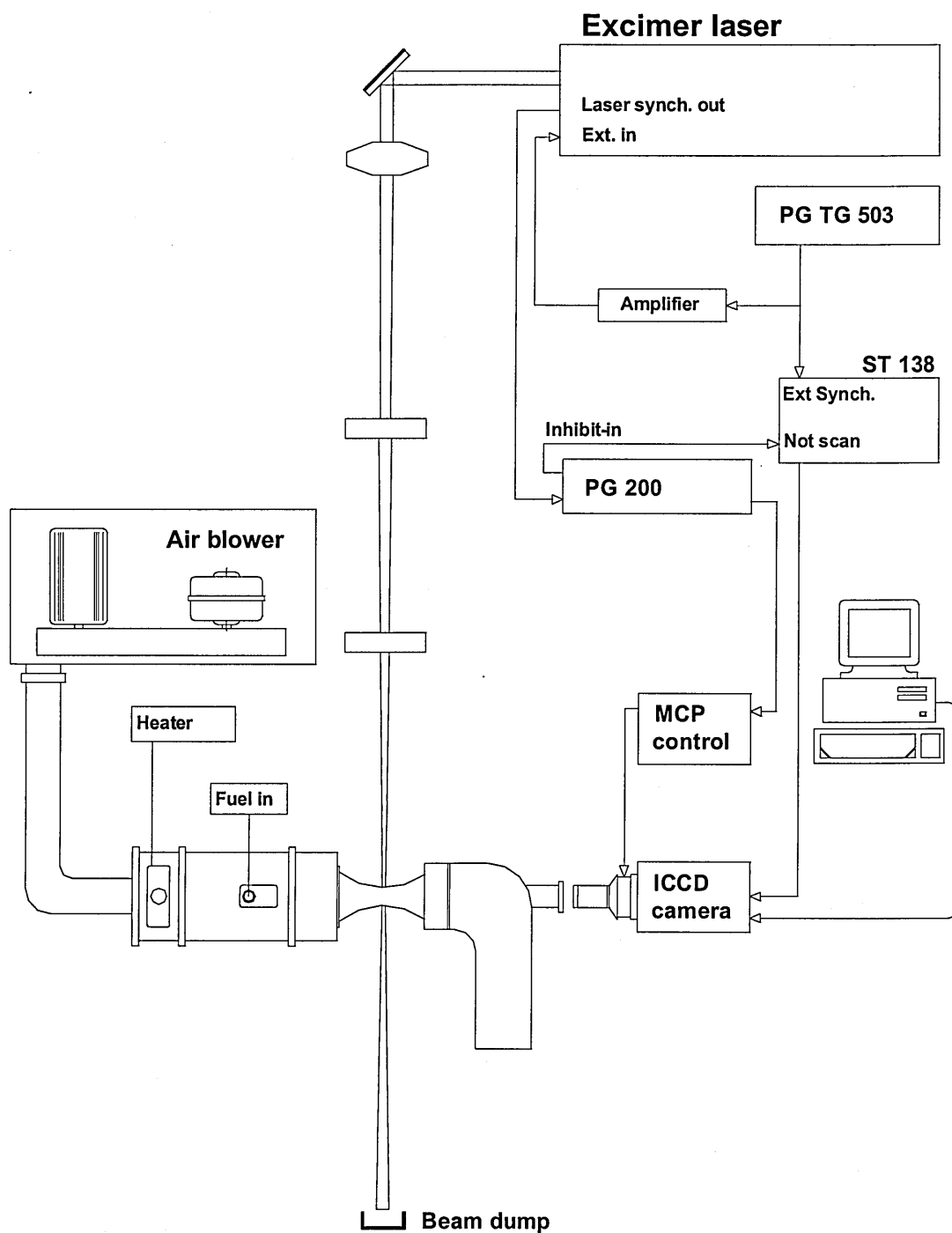


Figure 6.4 Schematic of the LPP rig experimental set-up

The timing and the synchronisation of the events was as follows: A pulse generator, Thander TG 503, sent a pulse to the controller unit of the camera (ST 138) and to the laser input simultaneously. This input signal triggered the laser which in turn sent a synchronised signal to the pulse generator PG 200.

This unit was necessary to control the delay and the gating of the intensifier on the CCD camera. The exposure time of the CCD chip (578x384 pixels) and the number of frames in the data acquisition were set by the imaging software on the computer.

During all experiments the laser was triggered at 1 Hz. This frequency was set at the source of the triggering circuit, i.e. the Thander TG 503. The gate delay was set to 1440 ns and the gate width to 100 ns. The fluorescence images were an average of 50 to 100 laser shots. The fluorescence was collected with a Nikon 60 mm macro lens f/2.8 connected to the ICCD camera.

6.3.2 Calibration experiments

A detailed calibration of the fluorescence signal of the naphthalene had to be carried out for this set-up. The air plenum chamber of the LPP rig was removed to allow the vaporiser to be inserted behind the fused silica duct. A similar arrangement is shown in Figure 4.7 (Chapter 4). The exit pipe of the vaporiser was placed at the centre of the optical duct as to provide closer representation of the experiments. The depth of the field was estimated to be around 80 mm. Therefore, the calibration which was carried out at the throat of the duct could also be applied to the two other planes.

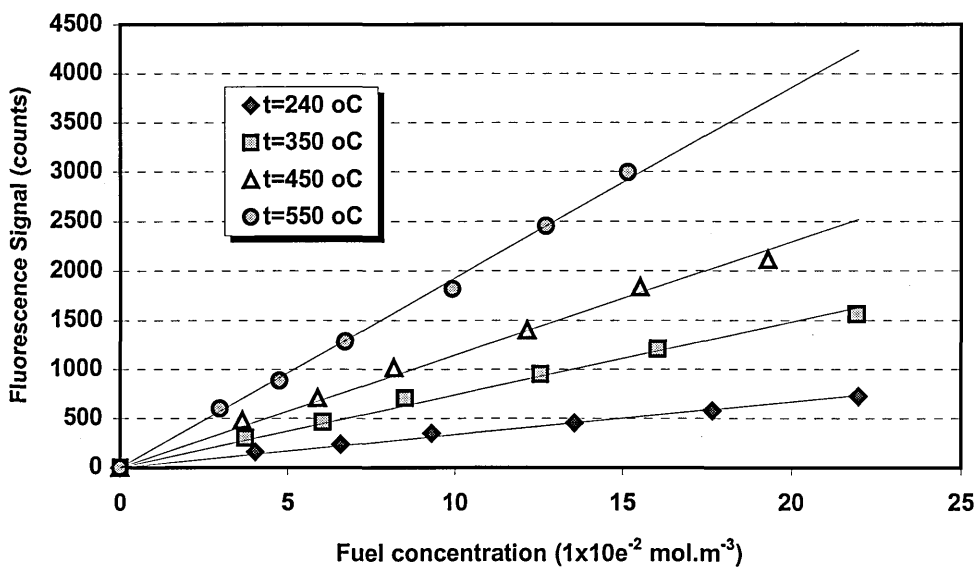


Figure 6.5 calibration curves for the fluorescence of naphthalene

This calibration was carried out while the final items of the premixer were being manufactured. The results of the calibration experiment is shown in Figure 6.5.

6.4 PLIF measurement results

6.4.1 Results of geometry 1

The results of the first geometry where both prefilms were long are presented and discussed next. The visual inspection of the duct revealed that liquid fuel could be seen at the exit of the inner prefilmer up to about the throat of the duct. This could be observed more easily at lower temperature and higher fuel flow rates. It must be reminded that the calibration procedure is valid under the assumption that the fuel is fully vaporised. Besides, due to problems related to quenching and estimation of local flame temperatures this calibration can be applied to the non combusting section of the flow. As a result, a semi-quantitative representation of the local equivalence ratio for this geometry is shown in Figure 6.6.

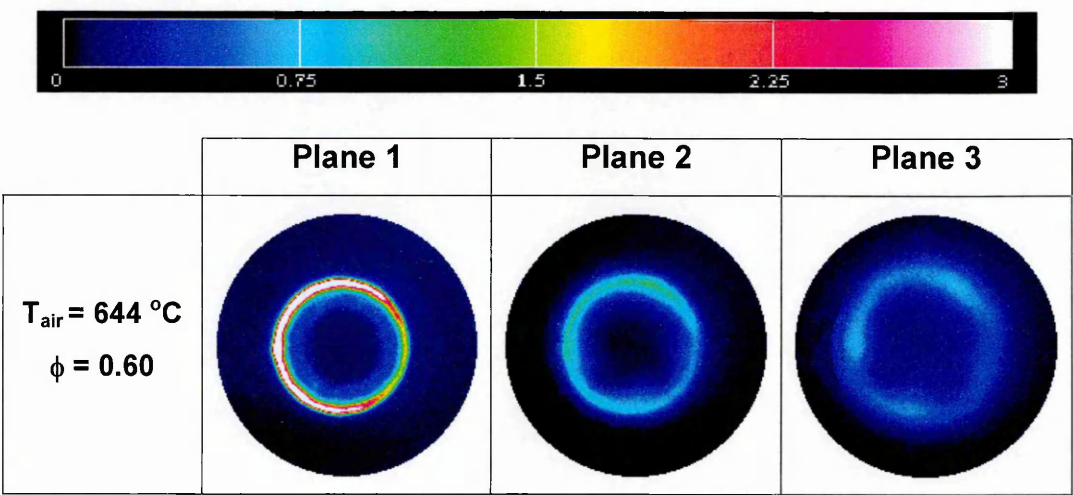


Figure 6.6 Semi-quantitative equivalence ratio of geometry 1

It can be seen that the strongest signal level are located around the inner prefilmer. In addition, the fuel remained in this central region through planes 2 and 3 and there was

little evidence of diffusion in other parts of the duct. The plotted equivalence ratio along the vertical centreline of the duct is shown in Figure 6.7. The internal diameter of the inner prefilmer is 24 mm. The peaks of the equivalence ratio were near this value and showed that the injected fuel was primarily attached to the prefilmer given the strong swirling motion of the air. It was also interesting to notice that the peak values were around $\phi = 3.0$ relative to the overall inlet $\phi = 0.60$.

In so far as liquid was present, even at the highest operating temperature, the fluorescence signal was believed to be overestimated. The fluorescence contribution of the liquid was an unknown and could not be quantified. Moreover, the fluorescence of the naphthalene was expected to increase with improved vaporisation. Thus, an increased signal level could be anticipated through planes one to three, given a gradual increase in the vaporisation of the fuel.

Nevertheless, with reference to Figure 6.7 a successive reduction in the peak values of the local equivalence ratios, from plane one to three, was observed. It was thus concluded that given the operational nature of the duct, the calibration procedure could not be applied accurately to the present case due to the interference of the liquid phase fluorescence.

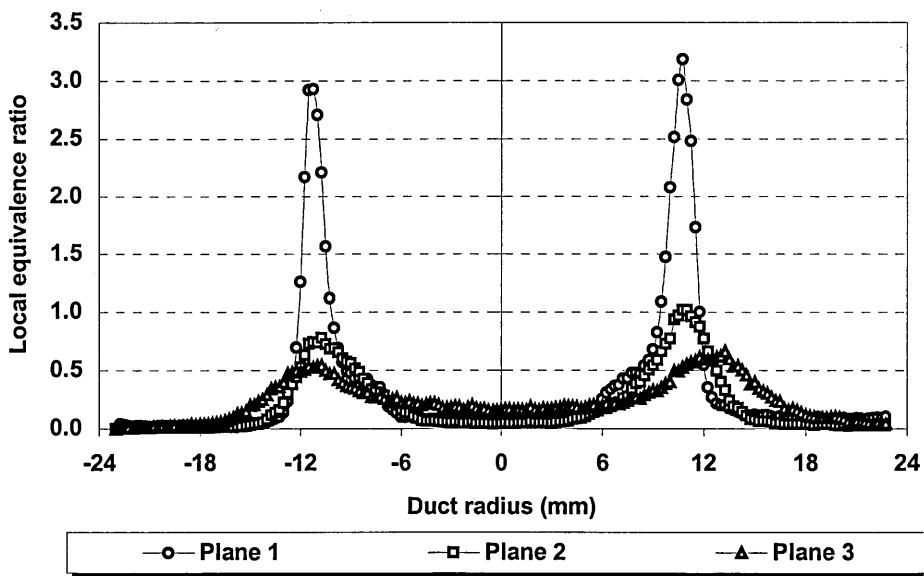


Figure 6.7 Plot of semi-quantitative equivalence ratio (vertical centreline)

This was further confirmed by examining the measured overall equivalence ratio both along the centreline of the duct and across the entire images of Figure 6.6. The results are shown in Table 6.3.

	Plane 1	Plane 2	Plane 3
ϕ_{overall} based on centreline	0.353	0.202	0.233
ϕ_{overall} based on entire image	0.348	0.165	0.198

Table 6.3 Variation of the overall equivalence ratio (inlet $\phi_{\text{overall}} = 0.60$)

The results showed that there was a reduction in the overall equivalence ratio from plane one to two and a slight increase from plane two to three. Consequently, it can be inferred that signal levels were overestimated at plane one and that the increase in the overall equivalence ratio at plane three was a direct result of the contribution of the increased fraction of the vapour phase and its signal.

Nevertheless, the overall equivalence ratio across the duct remained much weaker relative to the overall inlet condition of $\phi=0.60$. This was a speculative indication of insufficient vaporisation at this configuration.

Since, this problem was also encountered in other geometries it was decided to assess the operational characteristics and the mixture preparation of this LPP module under a qualitative form. The qualitative fluorescence of naphthalene for a range of inlet overall equivalence ratios, for this first geometry, is shown in Figure 6.8.

With reference to plane one and $\phi=0.30$, the 15 jets of the injector can be clearly distinguished. Although, there was an increased overall signal with increased equivalence ratio, the previously discussed reduction of signal level along the imaging planes could be seen. The overall trends of the duct were similar. However there were variations in the amplitude of these trends depending upon the inlet conditions.

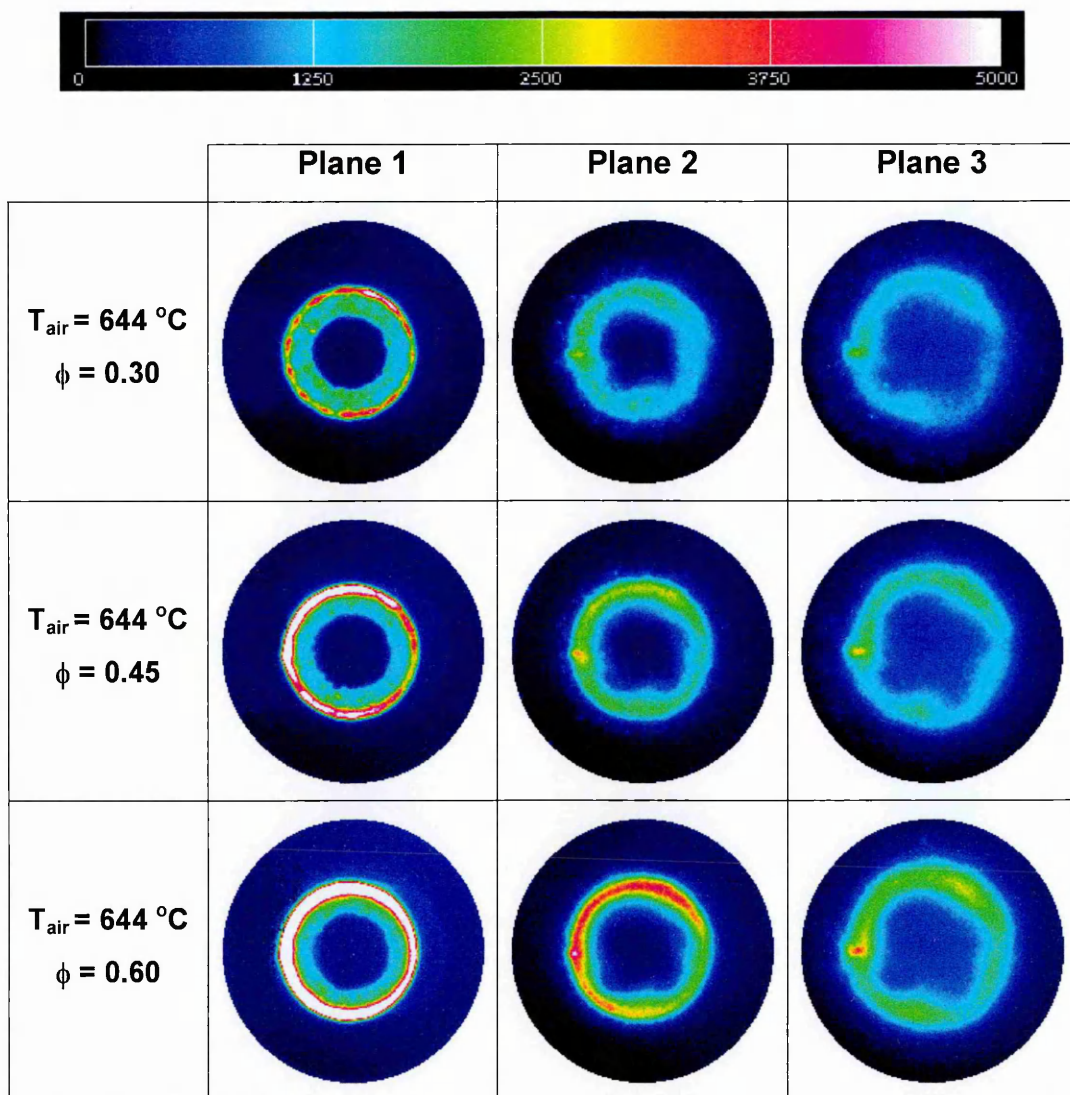


Figure 6.8 Fluorescence of naphthalene for various fuel flows (geometry 1)

Finally the position of the flame in the LPP duct is shown in Figure 6.9. The flame was stabilised further downstream of the throat of the duct. It is possible that the third plane of measurement may have been in the close vicinity of the flame front or indeed within the flame front. The fact that liquid fuel, to a large extent, was present in the duct could not have been anticipated. In addition the flame was believed to stabilise near the exit of the duct rather than within the divergent section.

Therefore, where the flame interference was not a critical issue in the measurements, the presence of liquid was a limitation. Inversely, near the exit of the duct where the

signal contribution of the liquid could have been assumed negligible, the presence of the flame was the limiting factor in quantifying the results.

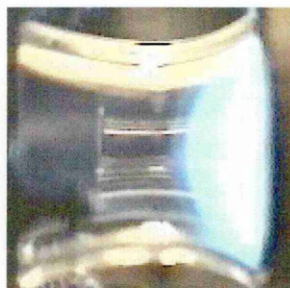


Figure 6.9 Flame position of geometry 1 ($T_{\text{air}} = 644\text{ }^{\circ}\text{C}$ and $\phi = 0.60$)

This was a further limitation of the calibration which could not be applied to the present case. The results of the remaining geometries are thus presented under a qualitative form. A video clip of this geometry is enclosed in a CD-ROM at the end of this thesis.

6.4.2 Results of geometry 2

The second tested geometry was similar to the first one but included a trimming of the inner prefilmer by 23 mm (see Table 6.2). The choice of this distance was based on visual inspection of the traces left by the fuel jets on the inner surface of the prefilmer. This trimming was carried out at the onset of the traces as to allow further penetration of the fuel and possible increased vaporisation. The effect of the temperature on the vaporisation of the fuel for a constant equivalence ratio, for geometry 2, is shown in Figure 6.10.

It could be seen that at the lower temperature of $T_{\text{air}} = 436\text{ }^{\circ}\text{C}$ the fluorescence signal was strongest at two locations, namely at the exit of the centre-body and the outer prefilmer. With increased temperature the signal levels at those locations were reduced, possibly due to a smaller contribution of the liquid-phase fluorescence. The spatial fluorescence signal, and thus vapour fuel, increased significantly between the centre-body and the outer prefilmer at higher temperatures. The fluorescence from the fuel jets could easily be observed at higher temperature whereas at the lower temperature, the fuel was primarily in liquid form and was entrained by the strongly swirling air flow and attached to either the centre-body or to the outer prefilmer.

At the second plane of measurement, there was some evidence of secondary atomisation from the tip of the outer prefilmer. LIF images showed droplet clusters between the outer prefilmer and the wall of the duct.

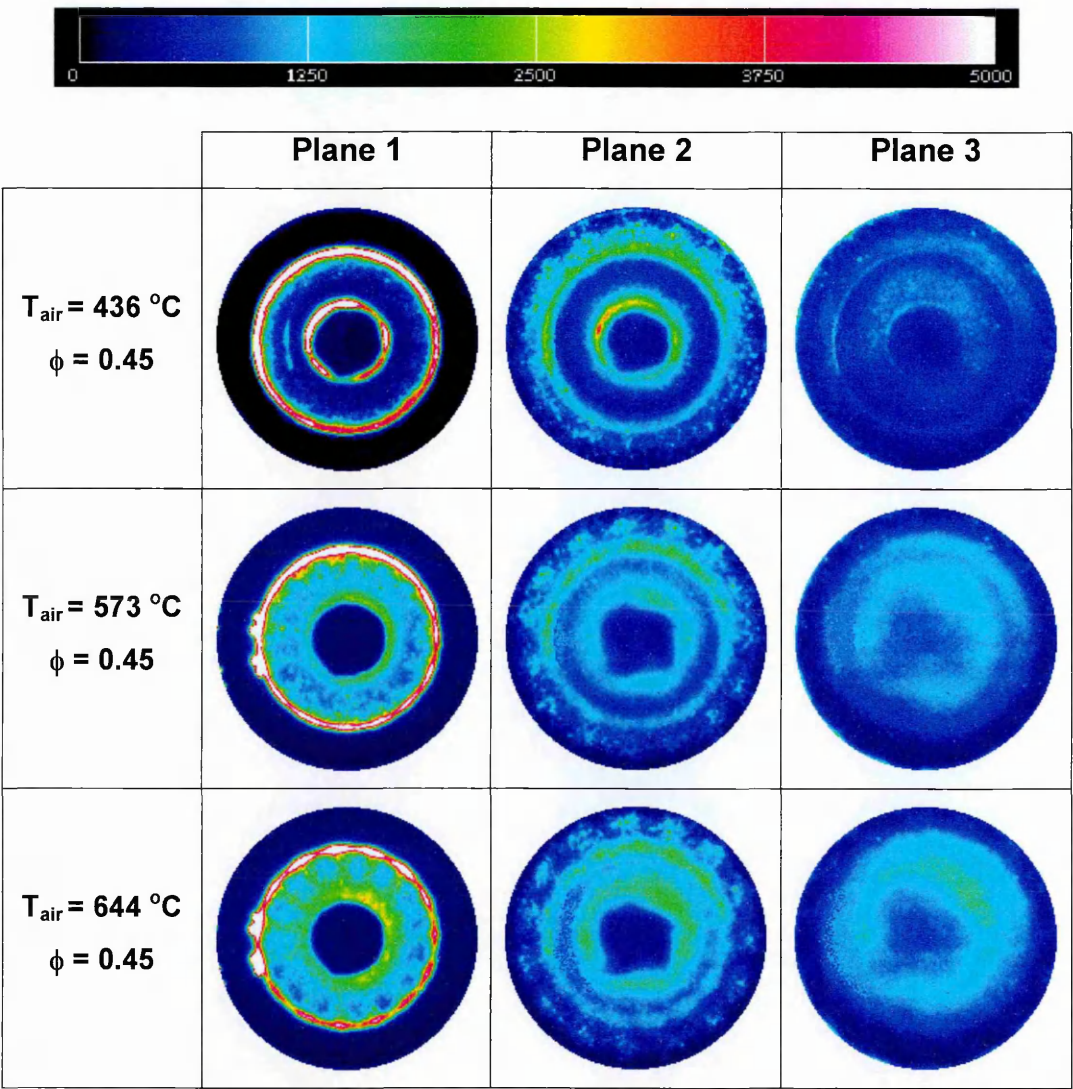


Figure 6.10 Fluorescence of naphthalene for various temperatures (geometry 2)

With respect to the influence of this shortened inner prefilmer on the flame position, little differences were noticed. However, the flame front was located slightly closer to the throat of the duct particularly at the lower air temperature. The flame structure for

this geometry is shown in Figure 6.11. A video clips is also included in the attached CD-ROM at the back of this thesis.



Figure 6.11 Flame position of Geometry 2 ($T_{air} = 644\text{ }^{\circ}\text{C}$, $\phi = 0.45$)

6.4.3 Results of geometry 3

In this geometry the inner prefilmer was trimmed further back by 19 mm (42 mm relative to the full length). The tip of the prefilmer was approximately 3 mm upstream of the injection plane, thus the prefilmer can be referred to as an air guide (see also Figure 6.3). The results are shown in Figure 6.12.

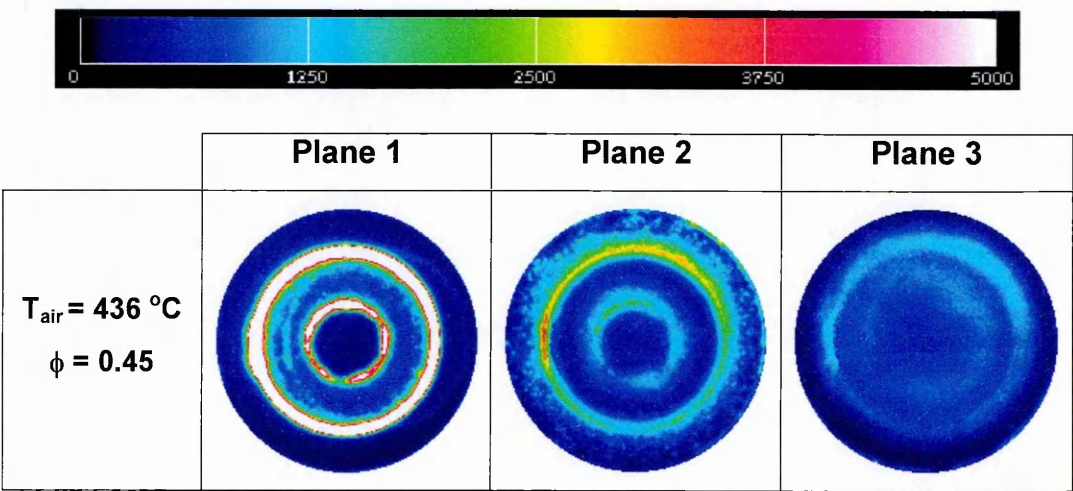


Figure 6.12 Fluorescence of naphthalene for geometry 3

As it can be seen the results were similar to that of the previous geometry for the same operating conditions, i.e. temperature and equivalence ratio. The fuel was once again found to be essentially located on the centre-body and on the inner prefilmer. This was also visible by the naked eye. Figure 6.13 shows the flame location in the LPP duct for this geometry.

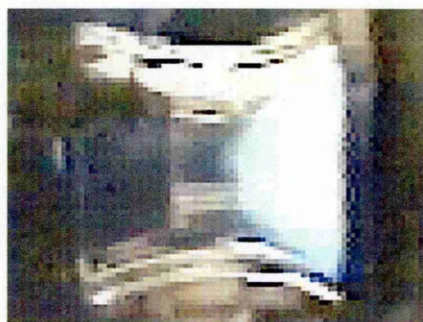


Figure 6.13 Flame position of Geometry 3 ($T_{\text{air}} = 436\text{ }^{\circ}\text{C}$, $\phi=0.45$)

Unlike geometry 1 and 2 where the flame front was stable, in this geometry there was a small flickering component of the flame which oscillated between the centre-body and the throat of the duct. This was captured in a high speed standard camcorder with capability of 120 frames per second (fps) and 2000 fps. The flame instability was attributed to the presence of the liquid by creating a fuel rich region. The tendency for the flame to flashback was highest at the centre and at a radius where respectively the centre-body and the outer prefilmer were located. This could clearly be seen in the video clip of this geometry (please refer to the video clip CD-ROM).

6.4.4 Results of geometry 4

In this geometry the outer prefilmer was trimmed by 20 mm to assess the influence of the outer channel on the spatial fuel distribution. The results at the first plane of measurement are presented in Figure 6.14. The fluorescence signal was strongest around the centre-body. However, some secondary atomisation was observed particularly at the lower air temperature and higher fuel flow. With increased temperature and reduced overall equivalence ratio, the fuel jets were found to collapse on the centre-body.

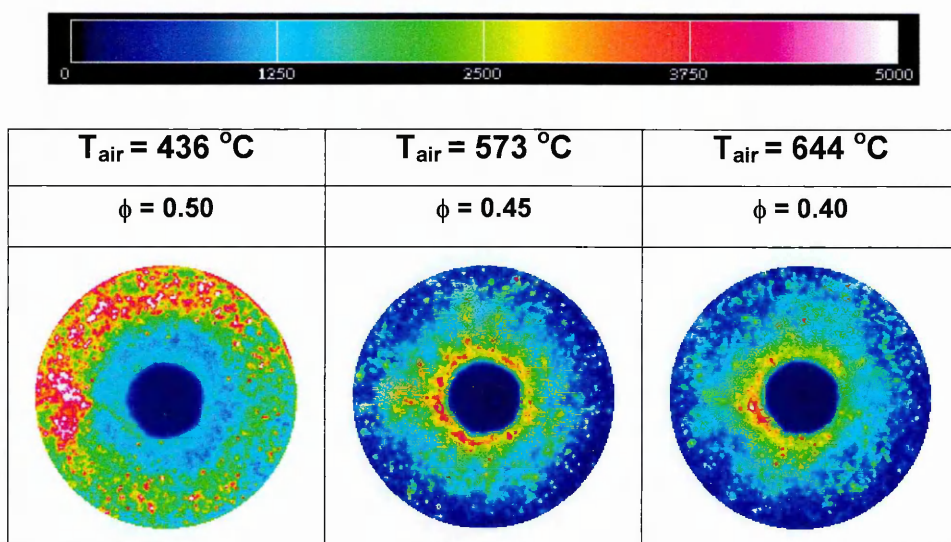


Figure 6.14 Fluorescence of naphthalene for geometry 4 (plane 1 only)

Since the outer prefilmer was shortened, the centre-body could be inspected visually. Indeed, this enabled to see 15 fuel streaks on the centre-body for all tested conditions of this geometry. As a result of the liquid being placed primarily at the centre of the duct, a relatively fuel-rich region was created and thus resulted in a reduced flame stand off distance. The flame became almost attached to the centre-body at low air temperature. The flame front was a few millimetres further downstream of the centre-body at leaner equivalence ratios and higher air temperatures.

Figure 6.15a and 6.15b show the flame position for the case where gradually the flame became attached to the centre-body. By examining carefully Figure 6.15b, some liquid can be seen at the tip of the centre-body. This feature was clearly captured in the video images and can be seen in the enclosed CD-ROM (clip entitled geometry 4a).



Figure 6.15a Flame position of geometry 4 ($T_{\text{air}} = 436\text{ }^{\circ}\text{C}$, $\phi=0.50$)



Figure 6.15b Flame attached to centre-body ($T_{\text{air}} = 436\text{ }^{\circ}\text{C}$, $\phi=0.50$)

However, at a leaner equivalence ratio and higher air temperature the flame was less prone to instabilities although it had a flickering component (see video clip geometry 4b, high speed imaging). Figure 6.16 shows the position of the flame for this condition.



Figure 6.16 Flame position of geometry 4 ($T_{\text{air}} = 573\text{ }^{\circ}\text{C}$, $\phi = 0.45$)

By removing the centre-body swirler assembly it also became apparent that the droplets seen in Figure 6.14 were partly due to the shear layer atomisation between the centre-body and the injector channel air flow. In addition, the fuel remained in the core region of the duct through planes 1 to 3. By removing the centre-body swirler, the overall air mass flow was increased by 36% for the same pressure drop (4%) across the combustor. Even though the internal air velocity field in both those cases were different, it was a good indication that the fuel remained essentially within the inner or the injection channel. This feature is shown in Figure 6.17.

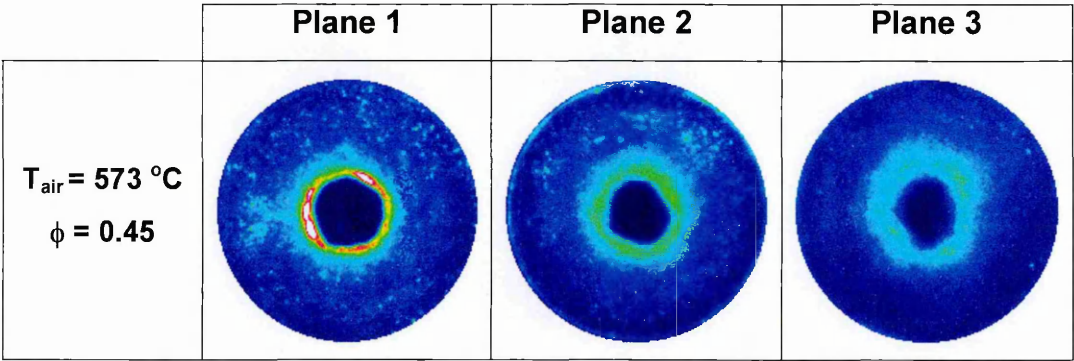


Figure 6.17 Geometry 4 with centre-body swirler removed

This result also suggested that the bulk of the fuel had little opportunity to break away from the injector channel.

6.4.5 Results of geometry 5

In geometry 5, both prefilms were cut back beyond the injection plane. In this case they both can be referred to as air guides rather than fuel prefilms. The result of this geometry is shown in Figure 6.18 and differed very slightly from geometry 4. However, the extent of the fuel attached to the centre-body was found to be the highest in this configuration.

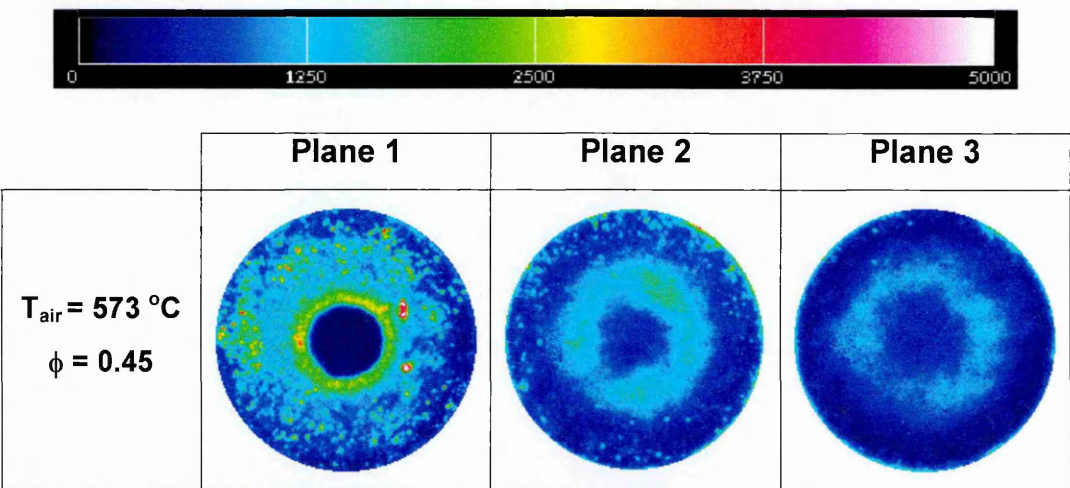


Figure 6.18 Fluorescence of naphthalene for geometry 5.

The fuzzy nature of the fluorescence image in the second and the third planes was due to the presence of the flame. The fluorescence of naphthalene was subjected to quenching by combustion products. In addition, some of the naphthalene molecules were likely to have undergone decomposition due to the high temperature of the flame. This decomposition combined with the consumption of naphthalene in the flame is believed to have resulted in a lower overall fluorescence signal.

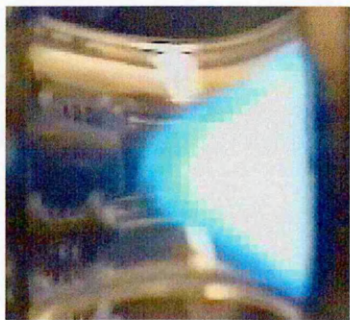


Figure 6.19 Flame position of geometry 5 ($T_{air} = 573\text{ }^{\circ}\text{C}$, $\phi=0.45$)

The flame position for this geometry is shown in Figure 6.19 details of which can be found in the video clips CD-ROM at the end of this thesis.

6.4.6 Results of geometry 6

In the first three geometries the fuel was found principally near the centre-body or the inner-outer prefilmer depending on the configuration. The fact that the trimming of the outer prefilmer resulted in the fuel being attached to the centre-body, suggested that the injector may be suffering from insufficient fuel jet momentum. As a result, it was decided to block a few of the holes of the injector to assess the characteristics of the premixer. The injector was thus reduced to a five hole configuration.

In addition, the flame stand off distance was reduced through geometry 1 to 5, i.e. it moved further upstream. Rather than starting from the initial configuration (both prefilms long) the shortest inner prefilmer or air guide was selected. Also, as a safety measure against flashback the outer prefilmer was trimmed only by 10 mm. The results of this geometry are shown in Figure 6.20. A strong fluorescence signal was observed at the exit of the prefilmer as shown by the images (5 streaks of fuel). It is also paramount to notice that there was almost no fuel around the immediate vicinity of the centre-body wall (see plane 1). However, there was fuel-vapour between the centre-body and the outer prefilmer as expected.

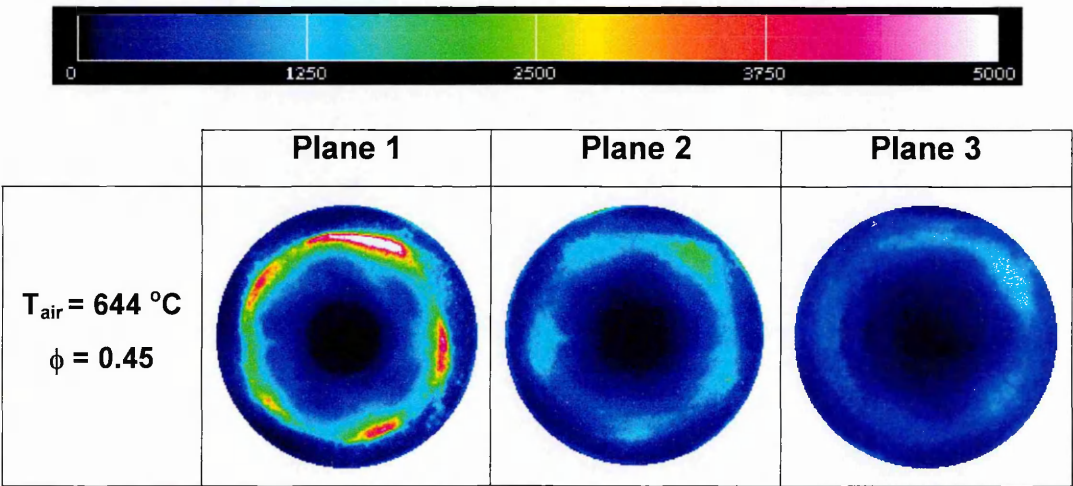


Figure 6.20 Fluorescence of naphthalene for geometry 6
(5 hole injector, outer prefilmer cut by 10 mm)

The flame position of this configuration for a slightly richer condition ($\phi=0.50$) is shown in Figure 6.21. It can be seen that the use of the longer outer prefilmer has resulted in the flame being stabilised further downstream of the throat of the duct. In addition, liquid fuel could be easily observed at the exit of the prefilmer. This was clearly captured in the video imaging of the flame. Two video clips of this geometry can be seen in the enclosed CD-ROM and include end views of the flame.

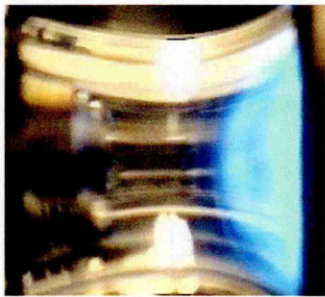


Figure 6.21 Flame position of geometry 6 ($T_{air} = 644\text{ }^{\circ}\text{C}$, $\phi = 0.50$)

This geometry not only resulted in insufficient vaporisation (abundant liquid fuel could be seen) but also in poor mixing. An image of the flame captured with high speed filming (2000 fps) and an instantaneous fluorescence image of the liquid-vapour fuel are shown in figure 6.22a and 6.22b.

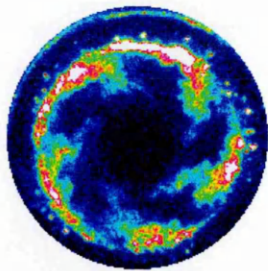


Figure 6.22a Single shot image of fluorescence (plane 1)



Figure 6.22b Instantaneous image of the flame (end view)

Although the flame was imaged further downstream relative to the first plane, the nature of the fuel distribution was conserved. The flame and the flow rotation were clockwise. For a more accurate description of the flame structure from a side and end viewing position please refer to the video clip CD-ROM at the end of this thesis.

6.4.7 Results of geometry 7

The outer prefilmer of the previous geometry was replaced by the short outer air guide as to allow maximum liquid jet penetration. In this configuration both prefilms were shortest and the fuel injector had 5 holes. The results of the fluorescence images are shown next in Figure 6.23.

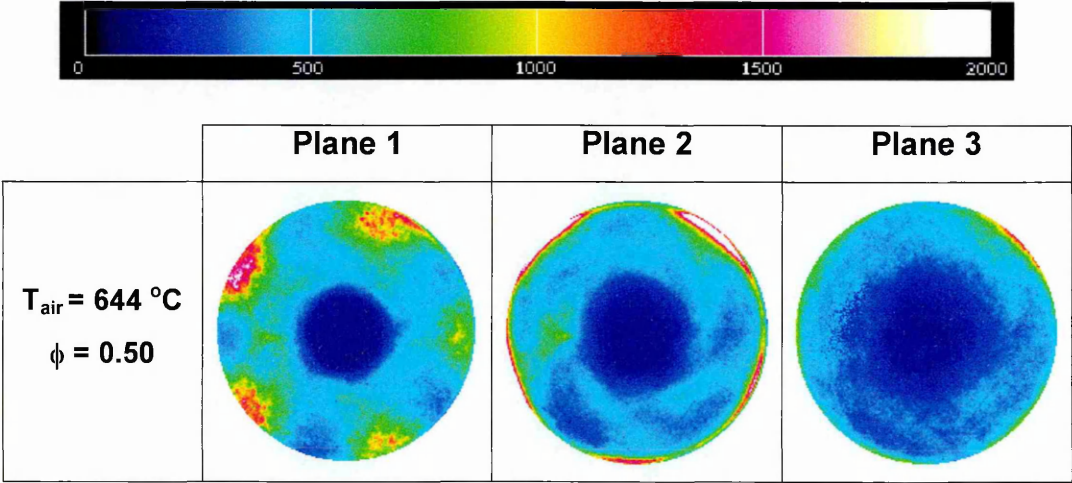


Figure 6.23 Fluorescence of naphthalene for geometry 7

It is important to notice that the colour scale is lower relative to the other geometries. It ranges from 0 to 2000 as opposed to 0 to 5000. The images show also a better spatial distribution of the fuel. Nevertheless, some liquid fuel could be observed along the wall of the duct. This can be seen at the outer edges of the image at the second plane of measurement.

There was also a small signal level around the centre-body. This geometry can be compared qualitatively with geometry 5.

Beyond minor operational differences in the flow conditions the underlying difference is a 5 hole injector compared with a 15 hole one (please refer to Figure 6.18). The flame position for this final geometry is shown in Figure 6.24.

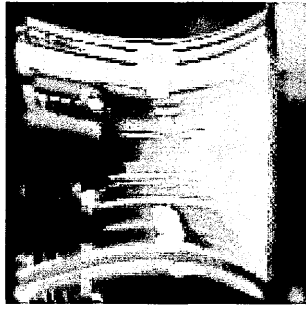


Figure 6.24 Flame position of geometry 7 ($T_{\text{air}} = 644\text{ }^{\circ}\text{C}$, $\phi=0.50$)

Although the flame was stabilised downstream the throat of the duct, it had a flickering component. Unlike geometry 5 where the latter was found to be only in the centre of the duct, this component of the flame was also observed near the wall of the duct. This may have been partly due to the presence of liquid along the boundary layer of the wall promoting this regime of flashback. Moreover, since liquid could be seen along the beginning of the wall of the duct, the flame was almost anchored to the exit diameter of the duct. This feature can clearly be seen in the end view video clip entitled geometry 7b. Another video clips showing the flame position in the duct is also provided (clip entitled geometry 7a).

6.5 Summary

An optical LPP combustor module was designed for non-intrusive PLIF measurements at atmospheric pressure. It featured a novel conical centre-body and a curved wall convergent-divergent premixing duct. The analysis of qualitative fluorescence images of the fuel concentration and the video imaging of the flame position in the LPP duct have been used to gain insight into the operational features of this LPP module. Several geometries were tested and the main findings of this experimental work are summarised next.

In configurations where either the inner or the outer prefilms were long the bulk of the vapour-liquid fuel was located near the internal surface of those prefilms. By gradually cutting those prefilms back, to allow further liquid jet penetration, the extent

of the fuel at or near the centre-body was increased. The geometry in which this was the most apparent feature consisted of both the shortest prefilmer. In this case the fuel jets were found to collapse on the centre-body wall.

Moreover, by progressively trimming the fuel prefilmer it was found that the flame stand off distance was reduced as the flame front moved further upstream. This was an aggravated problem at lower air temperatures and higher fuel flow rates. The worse condition with this respect was also the one which consisted of the shortest prefilmer.

As a result of the above observations and measurements, the fuel injector was modified from a 15 hole to a 5 hole configuration. With increased fuel jet momentum, thus further penetration, a better spatial fuel distribution was observed. Nevertheless, flame flashback was observed at the periphery of the duct compared with the central core region of the duct in a 15 hole configuration. In this new configuration some of the fuel was found on the wall of the premixing duct.

For the various tested geometries the overall mixing remained poor, although it has not been possible to quantify. Due to lack of quantitative data, given the presence of liquid and the interference from the flame, a qualitative assessment of the mixing was carried out. This assessment was based on the fluorescence images.

In order to gain a better understanding of the present LPP duct, further work was required. PDA and LDA measurements for characterising the liquid phase and the air flow velocity fields were estimated to be difficult to achieve. In effect, the wall curvatures of the duct were believed to give rise to refraction and astigmatism effects. In addition, a reasonably detailed mapping of the velocity fields would have constituted a lengthy process given the point-wise measurement nature of these techniques.

Consequently, to augment the usefulness of the present study it was decided to carry out CFD simulations of the main tested geometries. This would provide information concerning the internal aerodynamics of the duct complementary to the present experimental investigation. The results of those simulations are presented and discussed in the next chapter.

Chapter 7

CFD modelling of large engine LPP duct

7.1 Introduction

The attraction of performing CFD simulations for the large engine LPP duct, presented in this chapter, is double. First, it seeks to provide a complementary picture to the experiments for an improved characterisation of the above LPP module. This can be achieved by gaining knowledge about the air velocity field inside the duct. Based on this information the liquid jet penetration can then be schematically studied. The simulations presented in this chapter were performed using Fluent 5.3. The physical grid was created using Gambit 1.2. To start, a brief overview of the $k-\epsilon$ turbulence model is first presented. The results of the 2D and 3D simulations are then discussed and a preliminary liquid jet breakup study of both the initial injector (15 holes) and the modified version (5 holes) is carried out. The contribution and the limitations of the 2D and 3D simulations are discussed at the end.

7.2 Overview of the $k-\epsilon$ model

Computational fluid dynamics (CFD) modelling has been used in a wide range of industrial and non-industrial areas (Anderson, 1995). Typical examples include aerodynamics of aircraft, internal combustion engines and gas turbines, turbomachinery but also environmental engineering and meteorology. Among the classical turbulence models, the $k-\epsilon$ model is by far the most widely used and validated. This will be the only model discussed here as it has been used for the present simulations. This discussion is centred around the governing equations of the fluid flow and the effect of turbulence and random fluctuations on these equations. Time averaging of the instantaneous governing equations introduces additional terms, into the momentum equations, that require modelling. Closure of the time-averaged momentum equation is achieved through a turbulence model. All the simulations of the current work have been performed with the standard $k-\epsilon$ model.

7.2.1 Governing equations of motion

The Navier-Stokes equations and the continuity equation describe essentially the instantaneous motion of all fluids under all conditions. However, in order to be solved, these equations which constitute a set of complex partial derivative equations require simplification. These equations can be derived by applying the conservation of mass and Newton's second law to an infinitesimally small volume. The detailed derivation can be found in many CFD related textbooks, for instance by Anderson *et al.* (1984) and Versteeg & Malalasekera (1995). The equations of continuity and momentum, in a so-called tensor notation form, are respectively:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (7.1)$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial t_{ij}}{\partial x_j} + S_m \quad (7.2)$$

The convention of this notation is that, i or $j = 1$ corresponds to the x -direction, i or $j = 2$ corresponds to y -direction and i or $j = 3$ corresponds to the z -direction. The letters u and p represent the instantaneous velocity component and the instantaneous pressure respectively. S_m is defined as source term of momentum, per unit volume per unit time, and accounts for total external forces (body forces) applied to the system. For a Newtonian fluid the viscous stresses are proportional to the rates of deformation, i.e. velocity gradients. The viscous stress tensor t_{ij} , in the equation 7.2, is defined as:

$$t_{ij} = 2\mu s_{ij} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (7.3)$$

$$s_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (7.4)$$

where μ is the laminar viscosity. The generalised transport equation of any variable Φ , in a fluid, takes the following form:

$$\frac{\partial(\rho \Phi)}{\partial t} + \frac{\partial(\rho u_j \Phi)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_j} \right) + S_\Phi \quad (7.5)$$

The physical representation of the of the above terms respectively from left to right can be defined as: The rate of change (transient term), the convective term, the diffusive term and finally the source term of the variable Φ .

Although the exact solution of the governing equations of motion have been formulated through direct numerical simulation (DNS) their application to turbulent flows is impractical. For a successful application of the DNS the eddies need to be resolved both spatially and temporally. This requires mesh spacing and time steps which are beyond the current capability of the most advanced computers.

In an engineering context, the vast majority of the flows are turbulent, i.e. the flow velocity changes in an irregular and chaotic manner. Turbulent flows are characterised by the appearance of eddying motions of a wide range of length scales. An eddy is defined as an area of swirling fluid with a characteristic dimension referred to as turbulent length scale. In case of large eddies, the kinetic energy of the flow is dissipated through a process called vortex stretching. The presence of mean velocity gradients in sheared flows distorts the rotational turbulent eddies. Thus, large eddies are dominated by the inertia effects and the dimensions of the shear flow. On the other hand, viscosity dictates the smallest scale of motion which can occur in a turbulent flow. Therefore, small eddies are limited by the viscosity of the fluid.

One of the earliest approaches to the investigation of the turbulent flows was introduced by Reynolds (1842-1912) and made use of the time-averaged variable concept. Here, the instantaneous velocity is decomposed into a mean and a fluctuating component. In many engineering problems, the knowledge of time-averaged properties, such as mean velocities, mean pressures etc., are often satisfactory.

If $\bar{\Phi}$ is defined as the time-averaged of an instantaneous flow property Φ , and Φ' its time-varying fluctuating component then:

$$\bar{\Phi} = \frac{1}{\Delta t} \int_0^{\Delta t} \Phi(t) dt \quad (7.6)$$

$$\Phi = \bar{\Phi} + \Phi' \quad (7.7)$$

By substituting the equation 7.7 into the instantaneous continuity, momentum and transport equation for Φ , and some rearrangement the time-averaged form of the Navier-Stokes equations, known as the Reynolds equations, can be expressed as:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho} \bar{U}_i)}{\partial x_i} = 0 \quad (7.8)$$

$$\frac{\partial (\bar{\rho} \bar{U}_i)}{\partial t} + \frac{\partial (\bar{\rho} \bar{U}_j \bar{U}_i)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(2\mu \bar{S}_{ij} - \overline{\rho u'_j u'_i} \right) + \bar{S}_m \quad (7.9)$$

$$\frac{\partial (\bar{\rho} \bar{\Phi})}{\partial t} + \frac{\partial (\bar{\rho} \bar{U}_j \bar{\Phi})}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\mu}{\sigma_i} \frac{\partial \bar{\Phi}}{\partial x_j} - \overline{\rho u'_j \Phi'} \right) + \bar{S}_\Phi \quad (7.10)$$

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \quad (7.11)$$

The time-averaged momentum equation and the Navier-Stokes momentum equation have similar forms. However, by introducing the average properties of the scalar Φ , an extra term has appeared. This is a direct result of the time-averaging of the momentum equation which yields a term containing the correlation between two fluctuating components. This is usually referred to as the turbulent stresses or Reynolds stresses.

A similar term in the scalar transport equation exists and is referred to as the turbulent scalar flux (TSF). The former and the latter are shown next:

$$\bar{\tau}_{ij} = -\overline{\rho u'_j u'_i} \quad (7.12)$$

$$\text{TSF} = -\overline{\rho u'_j \Phi'} \quad (7.13)$$

Therefore, a turbulence model is required for closure of the above equations by modelling the Reynolds stresses and the turbulent scalar flux.

7.2.2 Boussinesq eddy viscosity concept

The concept of eddy viscosity is a fundamental part of many turbulence models. Experimental observations show that turbulence decays unless there is shear in isothermal incompressible flows. In addition, turbulent stresses increase with the mean rate of deformation. Thus, Boussinesq in 1877 proposed that the Reynolds stresses could be linked to the mean rates of deformation such that:

$$\tau_{ij} = -\overline{\rho u_i' u_j'} = \mu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (7.14)$$

Dimensional considering of the eddy viscosity shows a proportional relationship to a velocity scale (ϑ) and to a length scale (ℓ) such that:

$$\mu_t = C \rho \vartheta \ell \quad (7.15)$$

where C is a dimensionless constant of proportionality. The turbulent eddy viscosity was first related to k and ε by the Kolmogorov-Prandtl relation where C_μ is an empirical constant:

$$\mu_t = C_\mu \rho \left(\frac{k^2}{\varepsilon} \right) \quad (7.16)$$

7.2.3 Turbulent scalar flux prediction

The mixing length model can be used to predict turbulent of scalar quantities. The standard approach in modelling of the turbulent scalar flux, in the scalar transport equation, is achieved by the eddy diffusivity model (Γ_t represents a turbulent diffusion coefficient).

$$-\overline{\rho u_j' \Phi'} = \Gamma_t \frac{\partial \bar{\Phi}}{\partial x_j} \quad (7.17)$$

The introduction of the eddy viscosity concept and the eddy diffusivity model allow the determine of the turbulent stresses and the turbulent scalar flux necessary for the closure of the time-averaged Navier-Stokes equations.

7.2.4 The k-ε two equation model

It can be shown that the governing equation for the turbulent kinetic energy k , contains a term which in effect represents the conversion of the mean kinetic energy into turbulent kinetic energy. The dissipation of the turbulent kinetic energy is a result of the work done by the smallest eddies against viscous stresses. The rate of dissipation is of paramount important in the study of turbulence dynamics and is known as ϵ .

It is possible to derive an exact ϵ -equation from the Navier-Stokes equations. However, it contains many unknowns which are not measurable and other terms which require modelling. Therefore, the transport equation for the dissipation rate was derived from the generic transport equation and from the best understanding of processes causing changes to k and ϵ , primarily on an empirical basis. The standard model uses the following transport equations for k and ϵ respectively:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_i}(\rho k \bar{U}_i) = \frac{\partial}{\partial x_i} \left[\frac{\mu_t}{\sigma_k} \left(\frac{\partial k}{\partial x_i} \right) \right] + \left[\overline{\rho u_i u_j} \left(\frac{\partial \bar{U}_i}{\partial x_j} \right) \right] - \rho \epsilon \tag{7.18}$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial}{\partial x_i}(\rho \epsilon \bar{U}_i) = \frac{\partial}{\partial x_i} \left[\frac{\mu_t}{\sigma_\epsilon} \left(\frac{\partial \epsilon}{\partial x_i} \right) \right] + C_{1\epsilon} \frac{\epsilon}{k} \left[\overline{\rho u_i u_j} \left(\frac{\partial \bar{U}_i}{\partial x_j} \right) \right] - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \tag{7.19}$$

The physical meaning of the above equations can be expressed from left to right as the rate of change of k or ϵ , the transport of k or ϵ by convection, transport of k or ϵ by diffusion, rate of production of k or ϵ and finally rate of destruction of k or ϵ . There are a set of five constants for the k - ϵ model which have been determined by extensive data fitting for a wide range of turbulent flows. They are shown in Table 7.1.

C_μ	σ_k	σ_ϵ	$C_{1\epsilon}$	$C_{2\epsilon}$
0.09	1.00	1.30	1.44	1.92

Table 7.1 The standard k-ε model constants

The first constant C_μ is used in equation 7.18 of the turbulent eddy viscosity. Prandtl numbers σ_k and σ_ϵ connect the diffusivities of k and ϵ to the turbulent eddy viscosity. The two remaining constants appear only in the ϵ -equation.

7.3 Simulated cases and boundary conditions

As discussed in the previous chapter, the progressive trimming of the prefilmer resulted in two distinctive features. First, the flame was found to move upstream with a tendency to flashback and then the collapsing of the liquid jets on the centre-body became apparent. The simulated cases thus cover the above range of conditions (geometries 1 to 5). This is reminded in the next table.

Build	Inner prefilmer	Outer prefilmer
Geometry 1	Long	Long
Geometry 2	shortened	Long
Geometry 3	Shortest	Long
Geometry 4	Shortest	Shortened
Geometry 5	Shortest	Shortest

Table 7.2 Description of simulated 2D cases

A 3D simulation of the geometry 5 has also been carried and will be presented in the relevant sections. To avoid cumbersome data presentation, the results of the intermediate geometries where the inner or the outer prefilmer were shortened, i.e. geometry 2 and 4, are attached in the Appendix 8 and 9. All simulations were performed using Fluent 5.3 and the physical domain and meshing were created by Gambit 1.2. The simulations were restricted to an isothermal flow (non-combusting), with an air temperature of $T_{air} = 644\text{ }^{\circ}\text{C}$ and mass flow of 60.4 g.s^{-1} . For the 2D cases the flow was assumed to be axisymmetric and the standard k- ϵ model was employed.

7.4 2D simulation of the LPP duct

7.4.1 The plenum chamber

The plenum chamber is the section which is located between the LPP module and the preheater can combustor. It is used as the initiating domain for the modelling of the LPP module. It is convenient to start the simulation at this location as this chamber is effectively a drum with known flow characteristics. It was assumed that the flow was primarily axial and had a magnitude of 3.115 m.s^{-1} . The turbulence levels, due to the

combustion of the preheater, were assumed to be around 15% as measured by Monmont (1999). The exit of the domain corresponds to the exit of the radial swirlers. The velocity magnitude for this domain is shown in Figure 7.1.

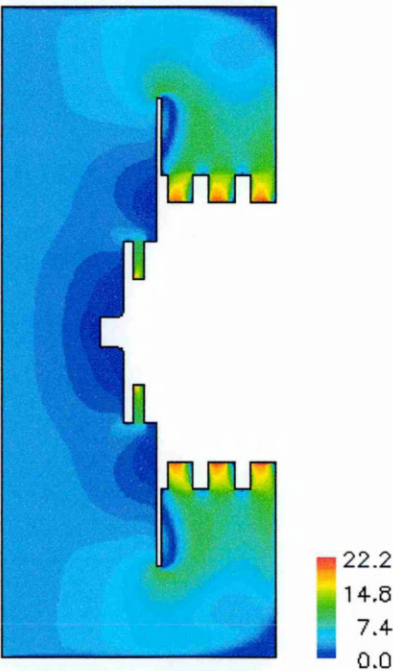


Figure 7.1 Velocity magnitude in the plenum chamber (m.s^{-1})

The velocity and the $k-\varepsilon$ profiles were used for inlet conditions of the premixing domain. As the flow at the inlet boundary was assumed to be axial, the swirling component of the flow (at the exit of the swirlers) was added to the above velocity profiles. The determination of the tangential velocity was based on the assumption that the flow in each swirler vane could be characterised as shown in Figure 7.2.

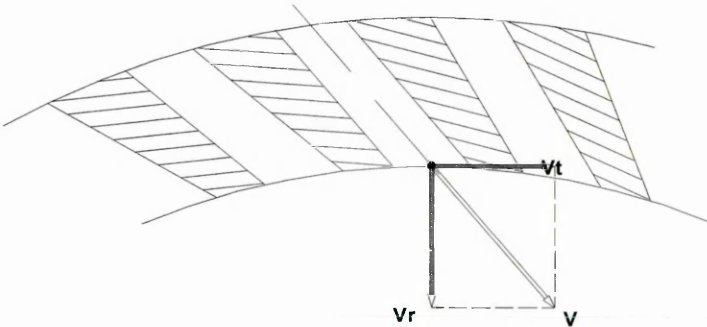


Figure 7.2 Schematic of air velocity components at exit of swirler

The swirl velocity (V_t or tangential velocity) was thus determined via the radial velocity (V_r) and the polar angle of the swirler. This added swirl velocity to the axial and radial velocity profiles, combined with the profiles of k and ε were used as inlet boundary condition for simulations in the premixing section.

7.4.2 Choice of grid density

Prior to simulating all the cases a preliminary study was carried out in an attempt to establish an independent solution relative to the grid density. Three different densities were tried with their corresponding plenum chamber sections. A partial view of the physical mesh for the geometry one is shown in Figure 7.3. The centre-body, the prefilers and the duct can clearly be seen.

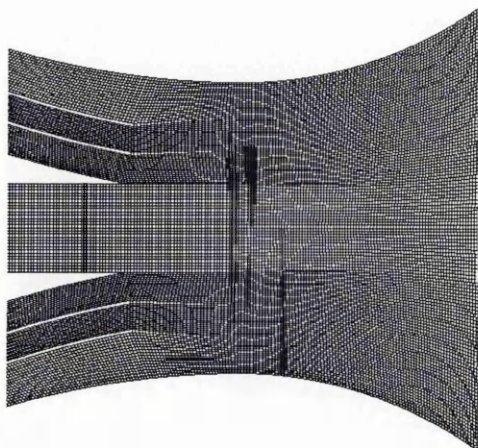


Figure 7.3 Structure of the dense grid for geometry 1

This initial assessment was carried out only for geometry 1 and the results are shown in Figure 7.4 to 7.6. The axial velocity contours of the case based on a coarse grid, containing only 16000 cells, shows a recirculation zone but in the dump combustor section. The fine grid which had 28000 cells showed improved signs on both the shape and the location of the recirculation. This was located at the divergent section of the duct as observed experimentally. Finally, the computed result for the dense grid (63000 cells) showed relatively little differences compared with the fine grid. The velocity magnitudes were very similar and the recirculation was found to occur slightly further upstream. Nevertheless, this density of the grid was used for the remaining geometries and constitutes a safer approach for reliable results.

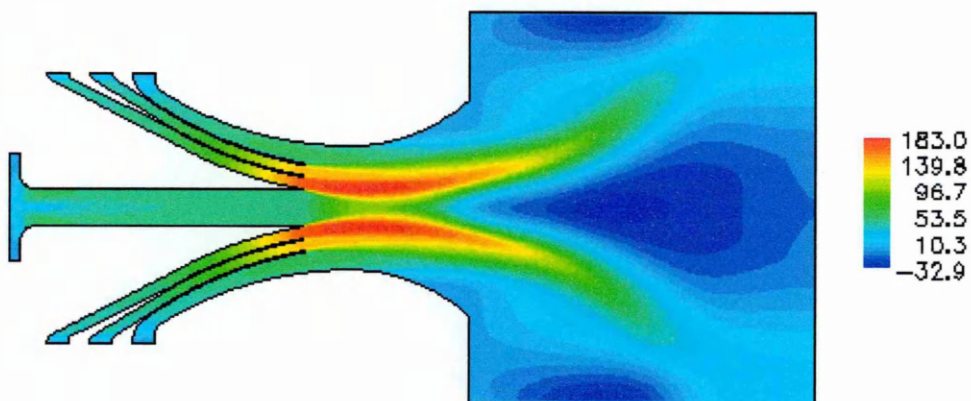


Figure 7.4 Axial velocity of geometry 1 (m.s^{-1})
(coarse grid, 16000 cells)

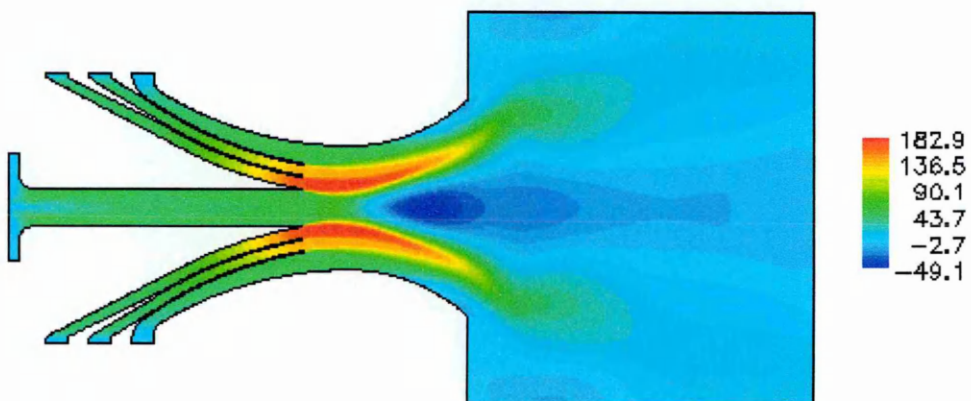


Figure 7.5 Axial velocity of geometry 1 (m.s^{-1})
(fine grid, 28000 cells)

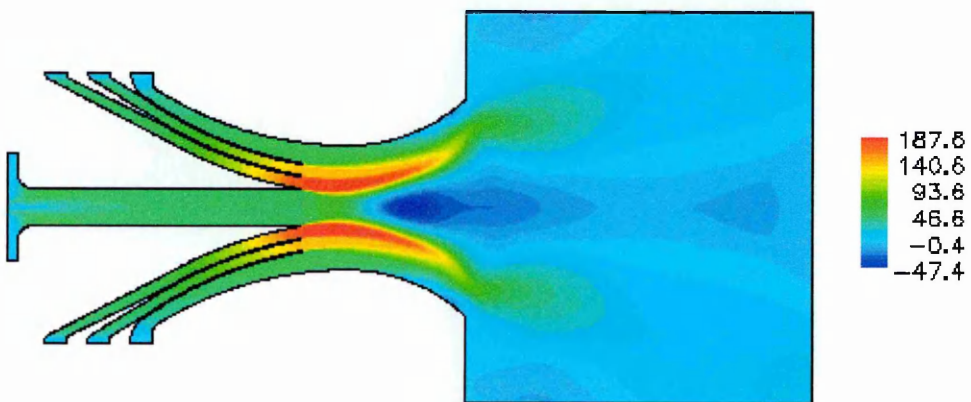


Figure 7.6 Axial velocity of geometry 1 (m.s^{-1})
(dense grid, 63000 cells)

7.4.3 Discussion of results

The simulation results of geometry 1, 3 and 5 are presented in the next few pages. For each geometry, the axial, radial and the tangential velocities are shown in Figures 7.7 to 7.15.

With regard to geometry 1 where both prefilms were long (Figures 7.7 to 7.9), it can be seen that the maximum axial velocity contours are found at the exit of the inner and the middle channel with a magnitude of about 190 m.s^{-1} . It is also interesting to notice that the centre-body axial air flow velocity is lower than that of the outer region of the duct. This is important because low core axial velocities can result in the recirculation moving upstream. There is also an important increase in the radial velocities in both those channels as a result of reduction of the radius. The swirl or the tangential velocity also increases slightly with a reduction of the radius and peaks at the exit of the prefilms. In strongly swirling flows, the air tangential momentum usually causes the air to flow radially outwards, creating a lower static pressure region at the centreline. The increase in the radial velocity at the divergent section of the duct and a strong swirl in this section have promoted a low pressure region. Consequently, a strong recirculation is found in this section. This recirculation consists of a toroidal shape where the flow is effectively reversed. The location of this recirculation is in reasonable agreement with the observation of the experimental case. In the experiments however, the flow was combusting and the heat release of the flame could substantially change the features of this flow reversal.

Geometry 3 with a short inner prefilmer (Figures 7.10 to 7.12) shows a similar position for the recirculation. The magnitude of the maximum axial velocity is lower in this case by about 10%. The peak values are at the exit of the prefilms but show smaller differences in magnitude between the inner and the middle channel relative to geometry 1. This is a direct result of the interaction of the flow from those channels. The magnitude of the radial and the swirl velocities have are relatively unchanged.

Geometry 5 with both prefilms short (Figures 7.13 to 7.15) shows a net reduction in the amplitude of the axial velocity. Although the recirculation seems to have been pushed downstream, its onset appears to have a similar location relative to the other geometries. The nature and the structure of the former is also very different. This result

is slightly surprising since the experimental evidence suggest a recirculation at about the throat level. The tangential velocity for the inner and the middle channel show a different profile and lower magnitude values. The radial velocity contour in the divergent section of the duct has lower values compared with the previous geometries and may explain why the recirculation has been established further downstream.

Although the velocity contours of Figures 7.7 to 7.15 provide an overall assessment of the internal aerodynamics of the premixer it is possible to analyse the velocity distributions in a more detailed approach. To this end, the velocity profiles were plotted for three different locations. Two planes normal to the injection point were chosen. The first one, 1 mm upstream and the second 15 mm downstream of this point in order to see possible interactions of the air flow channels. The plots for the inner, inner and middle and all channels for geometry 1, 3 and 5 respectively are shown in Figures 7.16 to 7.24. The distance along this plane is projected on the vertical y-axis. This was also carried out at the throat of the duct for all geometries.

Upstream the injection point, with reference to Figures 7.16 to 7.18, it can be seen that the axial velocity profile reduces through the inner to the outer channel. However, for the different geometries their values remain almost unchanged. The trend of the radial velocity profile is also similar. The strongest radial velocities are in the inner channel and reduce on the way to the outer channel. The swirl velocities are almost identical for all geometries. The strongest swirl can be seen in the middle channel. This is then followed by the inner channel and the outer one. This was expected since the inner, middle and the outer channels have swirlers with nominal angles of 45, 60 and 30 degrees. Therefore, there is little effect of prefilmer length on the air velocity profiles at the vicinity of the injection plane.

For the plane 15 mm downstream of the injection plane (Figure 7.19 to 7.21) the velocity plots show similar values for geometry 1 and 3. However for geometry 5, the values of the axial and the radial velocities are much lower. The profiles along this plane are much smoother when compared with the one upstream of the injection. The transition from one channel to the next proceeds in a more regular form. This can be attributed to the mixing of the air flow between each swirler passage. The swirl velocity is almost identical in the inner channel for all geometries. However, there is a slight

offset of the profile for geometry 5, from the middle channel towards the outer one. It can also be seen that the magnitudes of the axial and the tangential velocities have increased compared with the upstream plane.

At the throat of the duct, Figures 7.22 to 7.24, the velocity profiles are plotted from the centreline of the premixer to the wall of the duct. Geometry 1 and 3 present very similar profiles for all velocity components. The axial velocity profile for geometry 5 is almost uniform above 8 mm radius (the centre-body has a radius of 7 mm). The positive swirl velocity (Figure 7.24) is due to the counter rotating centre-body swirler.

7.4.4 Limitation of the 2D modelling

It is difficult to assess the accuracy of these simulations in the absence of experimental velocity data. Geometry 5 which is of interest has shown a very different recirculation zone and velocity profiles except near the inlet boundaries where the simulations were initiated. It must be reminded that the swirl was estimated from the radial velocity profiles based on the assumption of Figure 7.2. In addition, in an axisymmetric case it is assumed that there are no circumferential gradients in the flow.

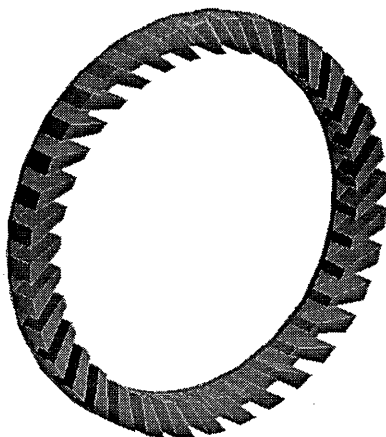


Figure 7.25 A CAD drawing of the 45 degree swirler

This is of limited relevance to the present case as gradients in the swirl velocity are expected to be present. The overall swirl is generated by discrete individual vanes as shown in Figure 7.25. It was thus decided to perform a 3D simulation of the premixer only for geometry 5 where both prefilers were short.

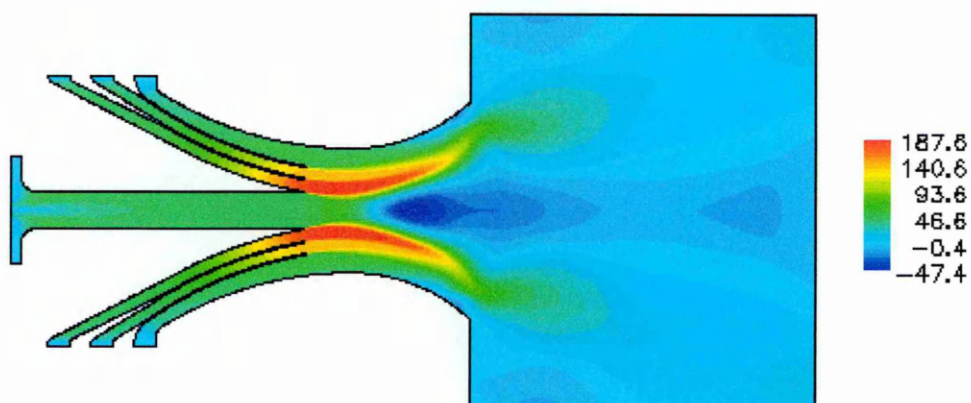


Figure 7.7 Axial velocity contours of geometry 1 (m.s^{-1})

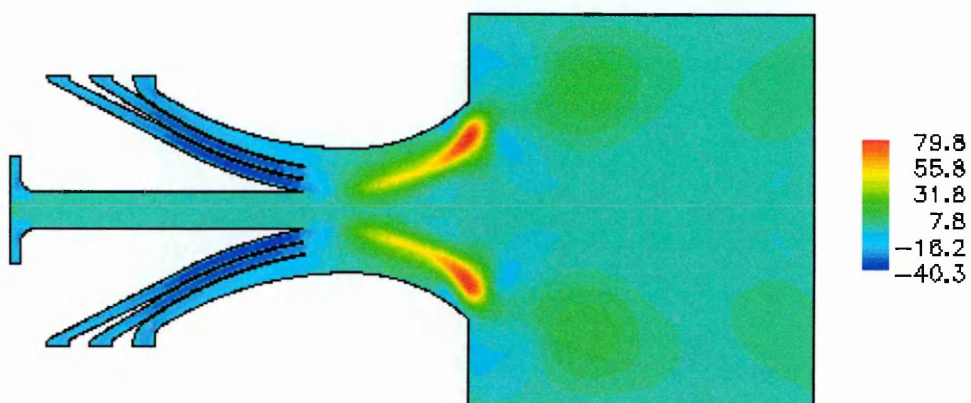


Figure 7.8 Radial velocity contours of geometry 1 (m.s^{-1})

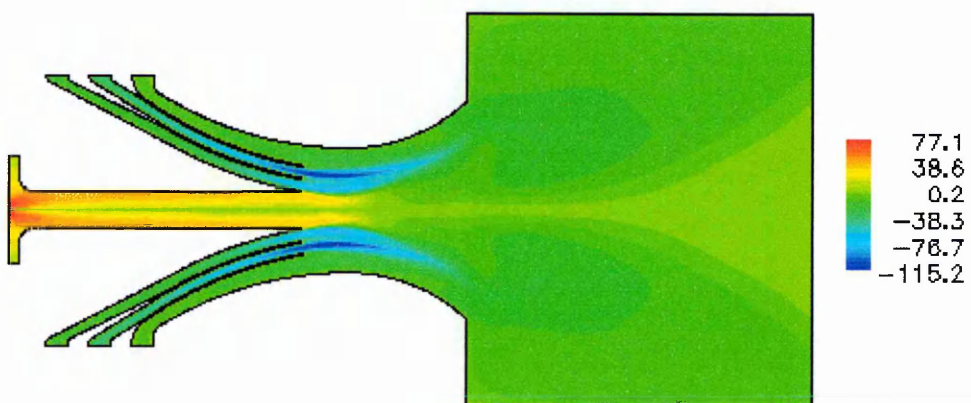


Figure 7.9 Tangential velocity contours of geometry 1 (m.s^{-1})

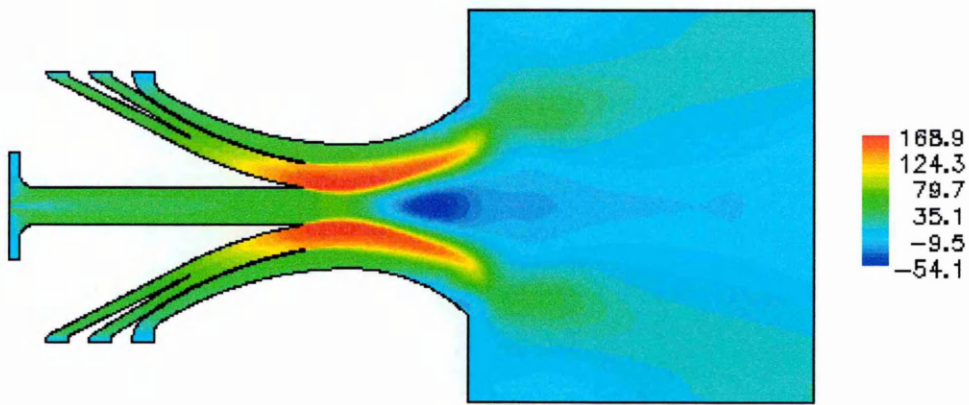


Figure 7.10 Axial velocity contours of geometry 3 (m.s^{-1})

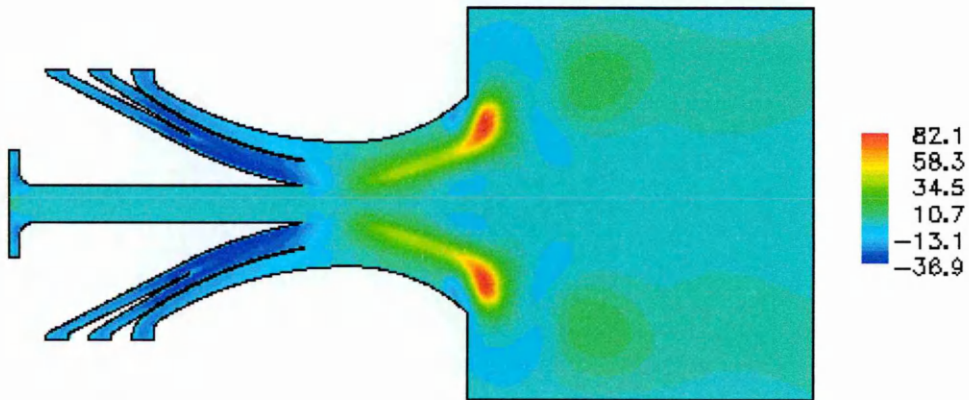


Figure 7.11 Radial velocity contours of geometry 3 (m.s^{-1})

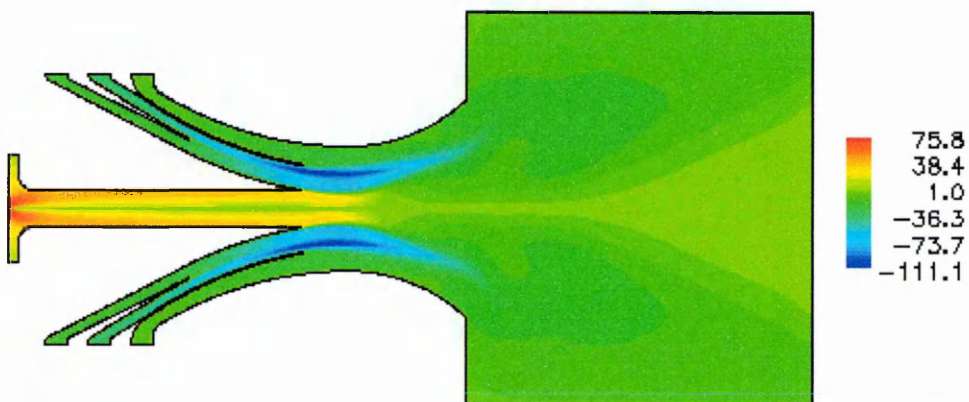


Figure 7.12 Tangential velocity contours of geometry 3 (m.s^{-1})

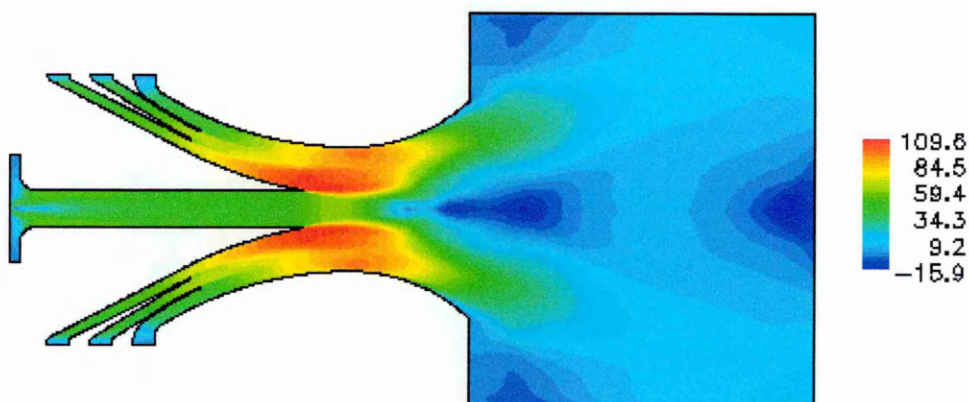


Figure 7.13 Axial velocity contours of geometry 5 (m.s^{-1})

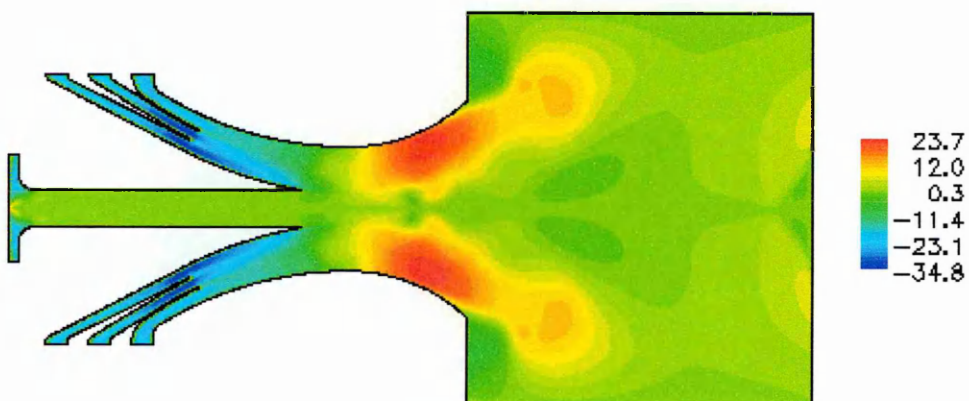


Figure 7.14 Radial velocity contours of geometry 5 (m.s^{-1})

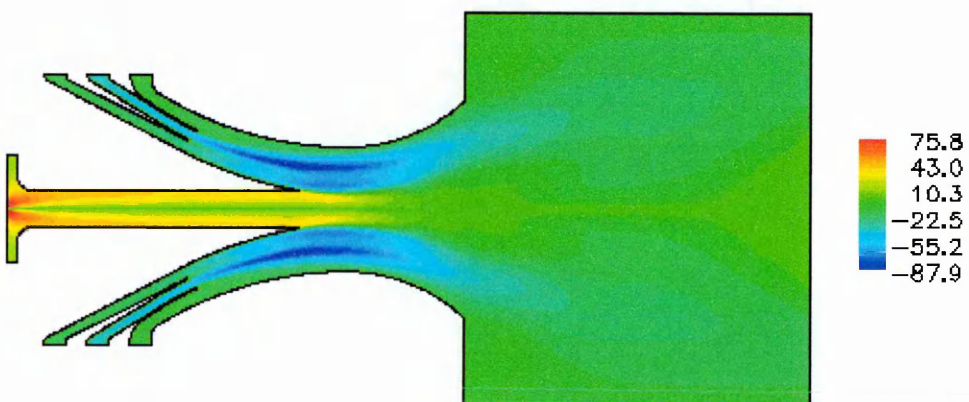


Figure 7.15 Tangential velocity contours of geometry 5 (m.s^{-1})

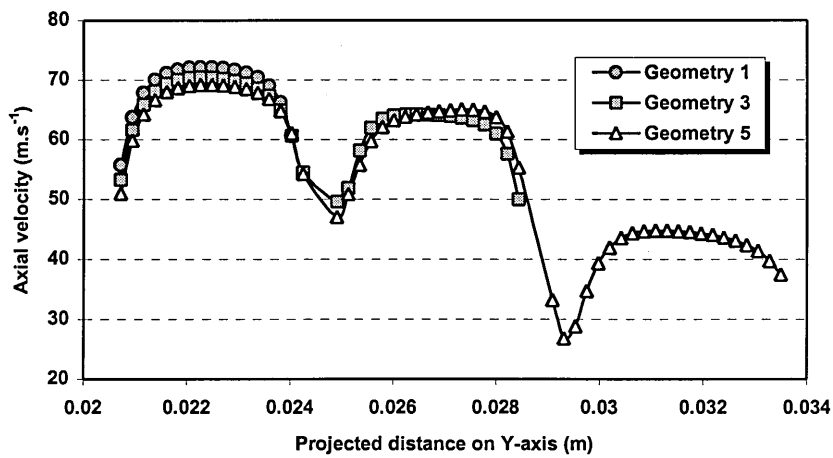


Figure 7.16 Axial velocity profiles (1 mm upstream of injection plane)

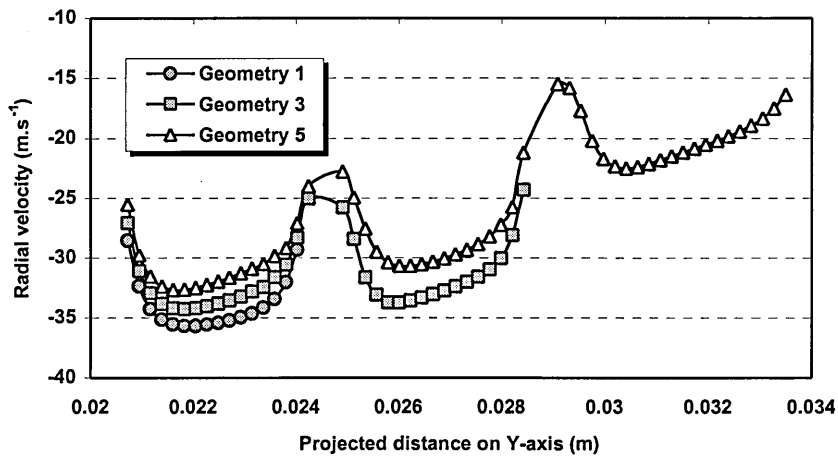


Figure 7.17 Radial velocity profiles (1 mm upstream of injection plane)

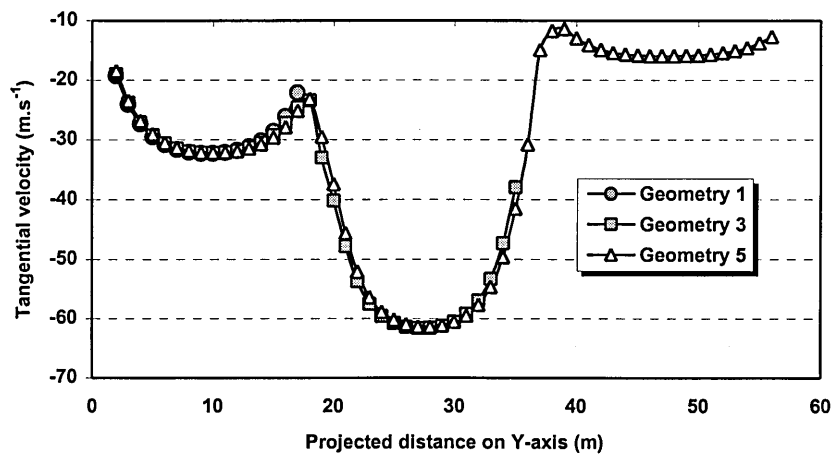


Figure 7.18 Tangential velocity profiles (1 mm upstream of injection plane)

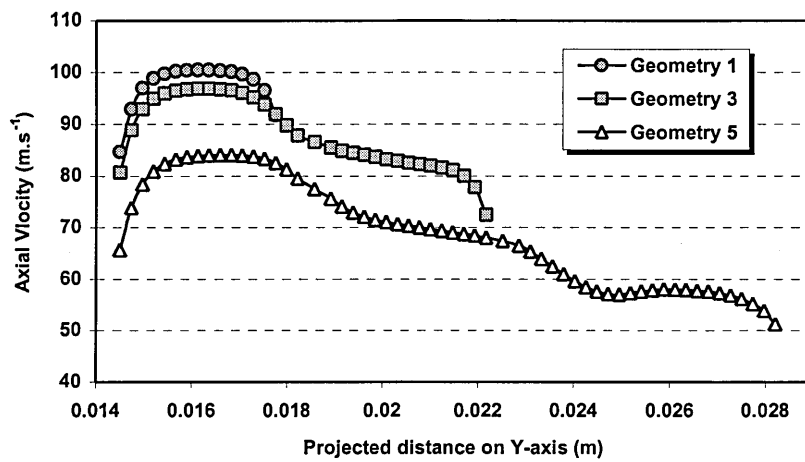


Figure 7.19 Axial velocity profiles (15 mm downstream of injection plane)

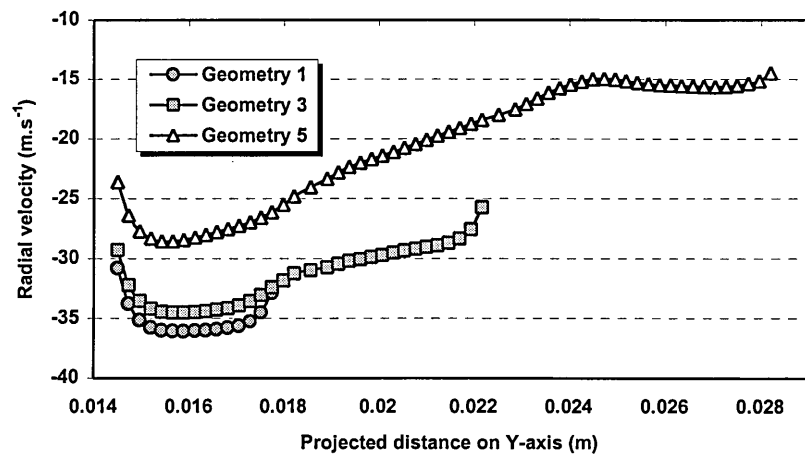


Figure 7.20 Radial velocity profiles (15 mm downstream of injection plane)

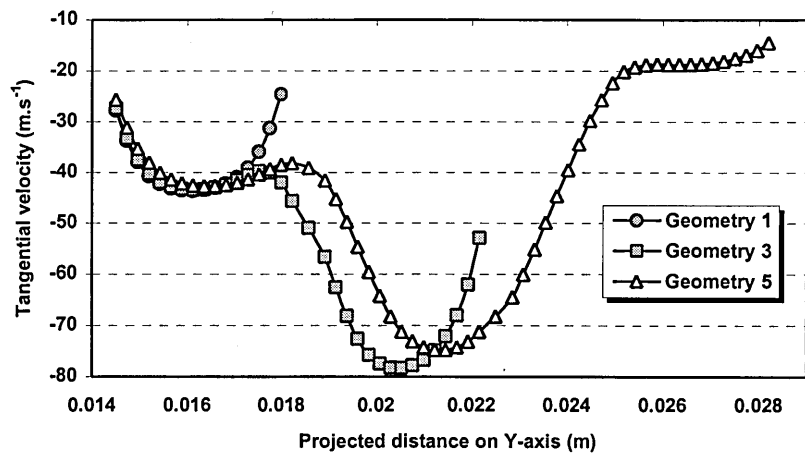


Figure 7.21 Tangential velocity profiles (15 mm downstream of injection plane)

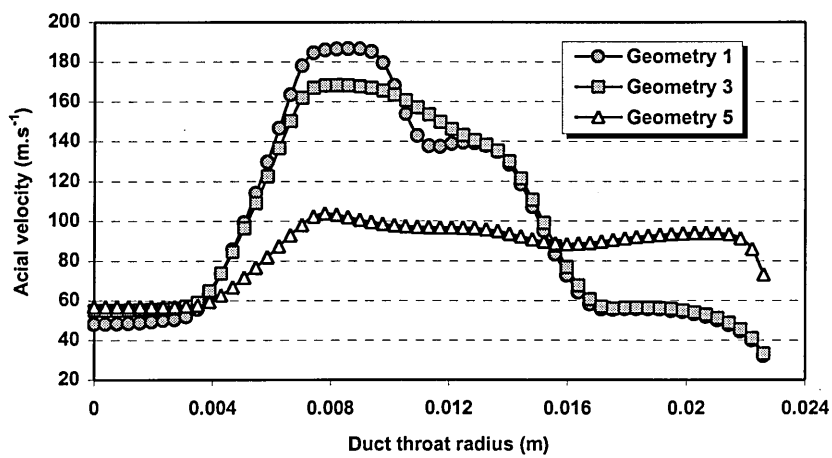


Figure 7.22 Axial velocity profiles (at the duct throat)

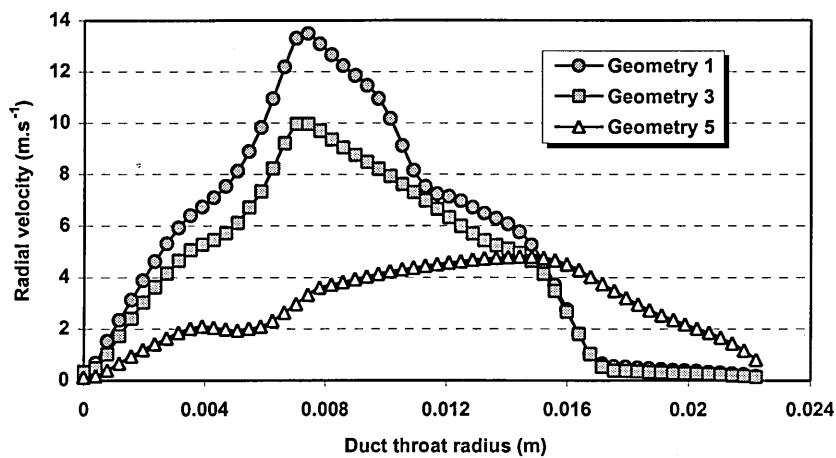


Figure 7.23 Radial velocity profiles (at the duct throat)

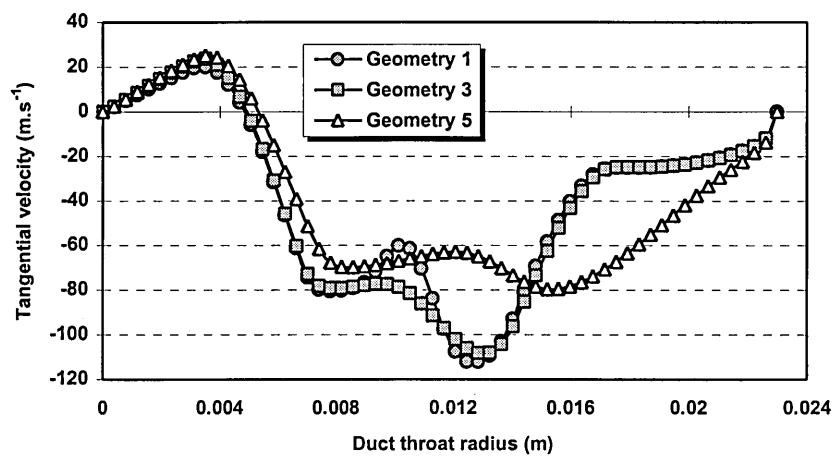


Figure 7.24 Tangential velocity profiles (at the duct throat)

7.5 3D simulation of the LPP duct

The 3D simulations were also initiated from the plenum chamber of the rig. Although, in the 2D simulations the entire domain could have been modelled as one unit, the splitting of the volumes in 3D has been necessary. This was first due to hardware limitations (processing memory) and then as a result of constraints in generating the mesh for the computational domain. The following sections detail the results of each element of the simulation domain.

7.5.1 The plenum chamber

The plenum chamber section is shown in Figure 7.26. This section includes the individual swirler vanes of each radial swirler. The counter rotating centre-body swirler can clearly be seen. In addition, the sign convention for the flow rotation is positive for an anti-clockwise rotation about the x-axis and negative for a clockwise rotation.

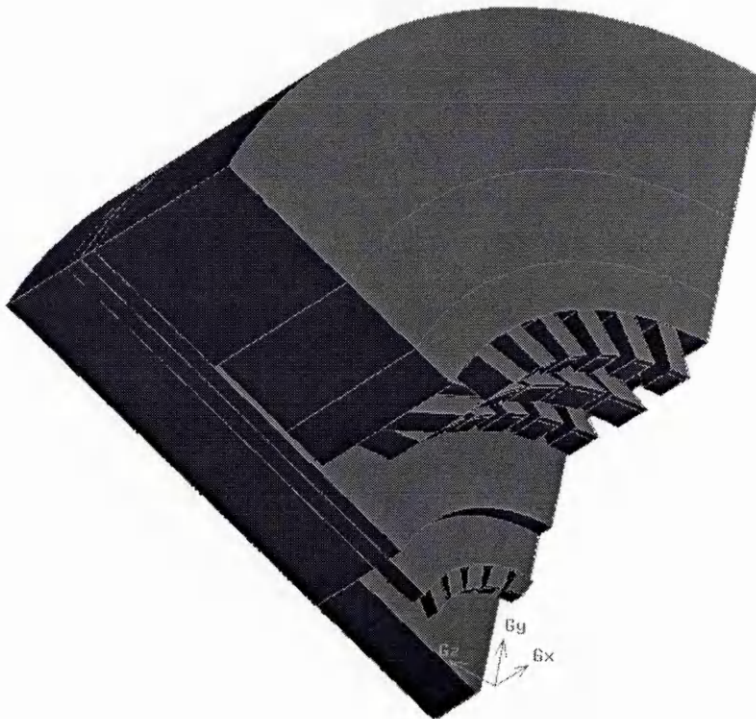


Figure 7.26 The modelled sector of the plenum chamber

The domain contains about 509,000 cells and each swirler vane for the centre-body, the 30, 45 and the 60 degree swirler contains respectively 80, 450, 600 and 850

hexahedral cells. The tangential velocity contours at the exit of each swirler vane of the modelled domain are shown in Figure 7.27. The row from left to right of this figure corresponds respectively to the centre-body swirler, the 45, 60 and 30 degree swirlers.

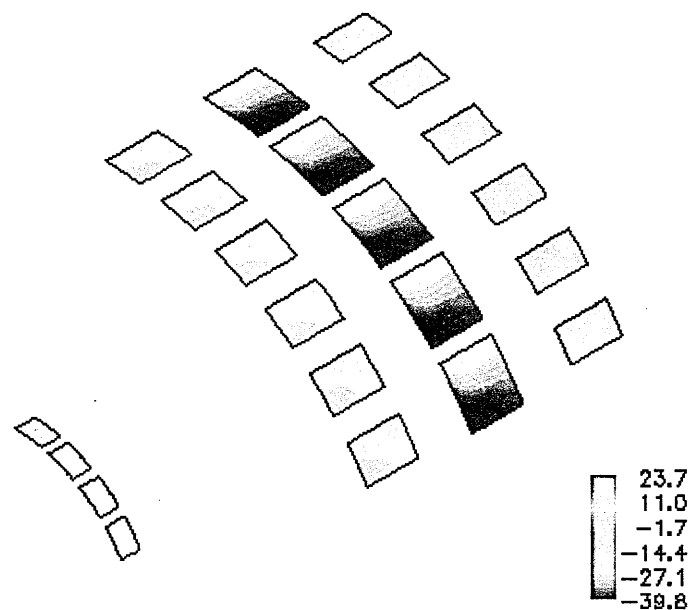


Figure 7.27 Swirlers exit tangential velocity contours

It is clear from the above figure that there is velocity profile at the exit of the swirlers. Therefore, the axisymmetry assumption of the 2D simulations is a restrictive approach to the modelling of the premixer. Moreover, there are changes in the geometry which are likely to contribute to the circumferential velocity gradients. The axial, radial and the tangential velocity profiles and the profiles of k and ε were used as input boundary conditions for subsequent parts of the simulation domain.

7.5.2 The “elbow” section

The so-called elbow section connects the exit of the centre-body swirler to the axial and core section of the centre-body. This volume had to be split in order to facilitate the meshing of the domain. This section was made of about 12,000 elements generated with a tetrahedral meshing scheme.

As in the previous case, the velocity profiles and the k and ε profiles were written to a file which was used for inlet conditions of the centre-body section. The result of the

simulation for the axial velocity distribution, at the exit of the swirlers (inlet to the elbow) and for the periodic boundaries, is shown next in Figure 7.28.

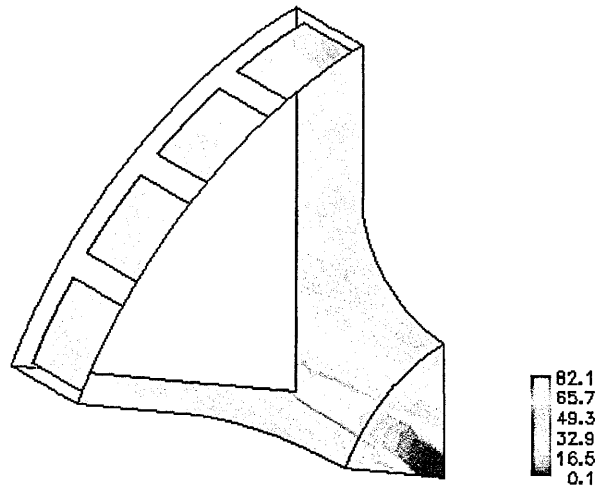


Figure 7.28 Axial velocity field in the elbow section (m.s^{-1})

7.5.3 The premixing section

As mentioned earlier, only the final geometry (with both prefilers short) was simulated in 3D. It consisted of a 60 degree sector and contained about 509,000 elements. This was considered to be a sufficiently dense grid and was the only simulated case. However, for presentation purposes a 240 degree sector is presented next. The axial, radial and tangential velocity contours are shown in Figures 7.29 to 7.31.

With reference to the axial velocity contours (Figure 7.29) it can be seen that there are two distinctive recirculating zones. One in the dump combustor section and the other in the divergent section of the duct. The location of the latter is in good agreement with the experimental observations. This recirculation is surrounded by a positive velocity field and is a likely feature. In effect, the end view video clips and the fluorescence images of geometry 5 show a hollow toroidal flame structure (please refer to Figure 6.18 planes 2 and 3 and video clips of geometry 6 and 7).

A more detailed discussion of the results compared with the corresponding 2D simulation is provided next.

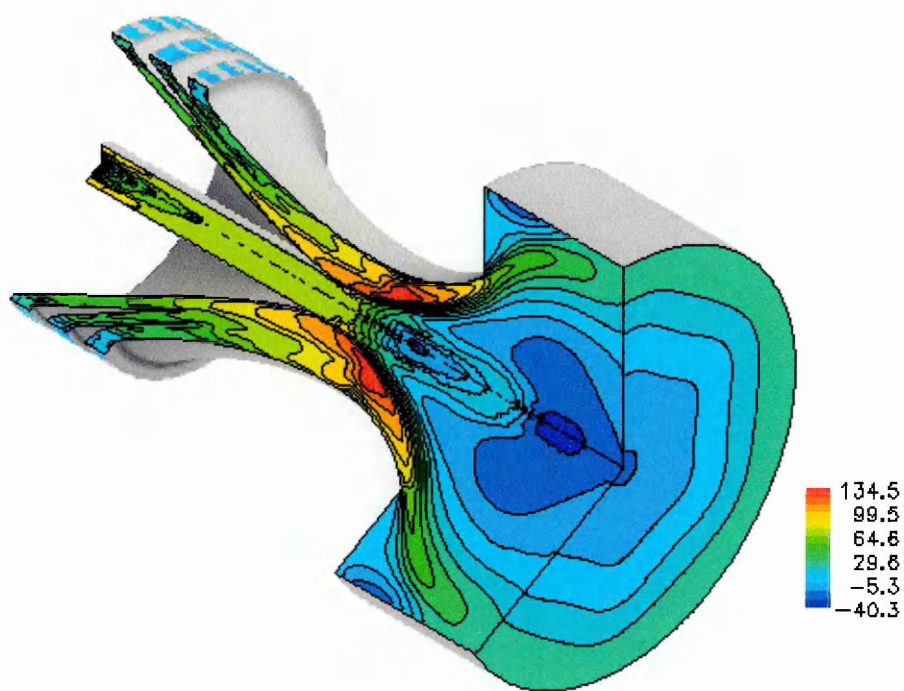


Figure 7.29 Axial velocity field of geometry 5 (m.s^{-1})

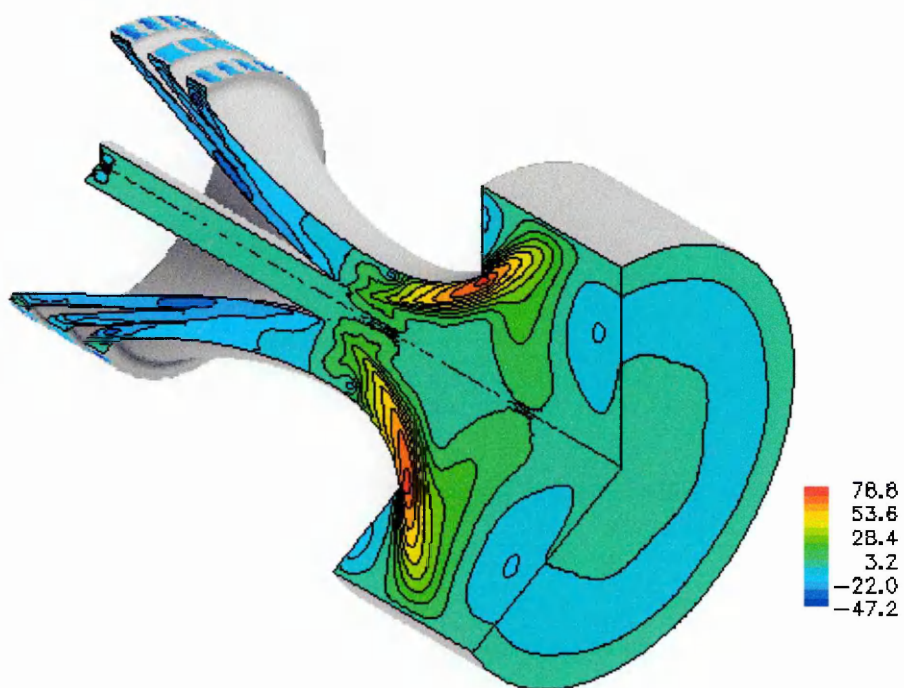


Figure 7.30 Radial velocity field of geometry 5 (m.s^{-1})

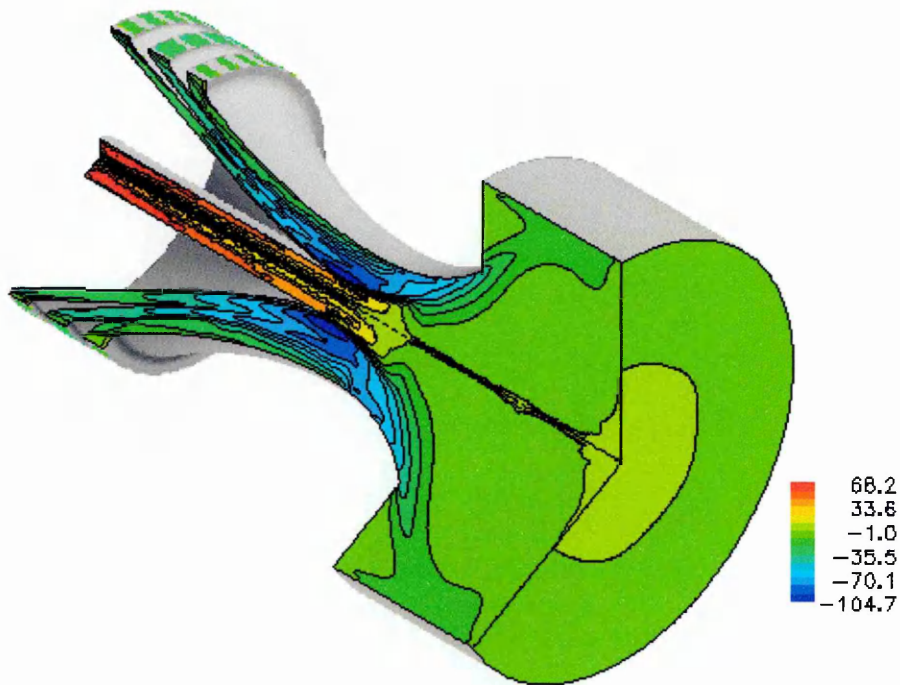


Figure 7.31 Tangential velocity field of geometry 5 (m.s^{-1})

7.5.4 Comparison of 2D & 3D results

The premixing section results allow a direct comparison with the 2D simulation shown in Figures 7.13 to 7.15. It can be seen that in the 3D case the amplitude of all components of the velocities were higher. For instance, the maximum axial velocity in the 2D and the 3D cases were respectively 109.6 m.s^{-1} and 134.5 m.s^{-1} . The recirculation in the 3D case has also a much stronger reverse axial flow associated to it. In order to locate the exact onset of the recirculation, the axial velocity profile along the centreline of the premixer was plotted for both cases and is shown in Figure 7.32. Although the initial velocity at the start of the domain is identical for both cases, the 3D simulation predicts higher axial velocities within the core of the centre-body.

The axial velocity then drops rapidly from the location where the centre-body and the main flow air streams meet. This reduction is expected since the centre-body swirler flow is counter rotating relative to the main air flow. The throat of the duct is at a distance of 127 mm from the start of the domain. The first negative axial value for the 3D and the 2D simulations were found to be respectively at 134 and 148 mm along the

axis. Thus, the 3D simulations suggests a recirculation 7 mm downstream of the throat whereas this distance was 21 mm in the 2D case.

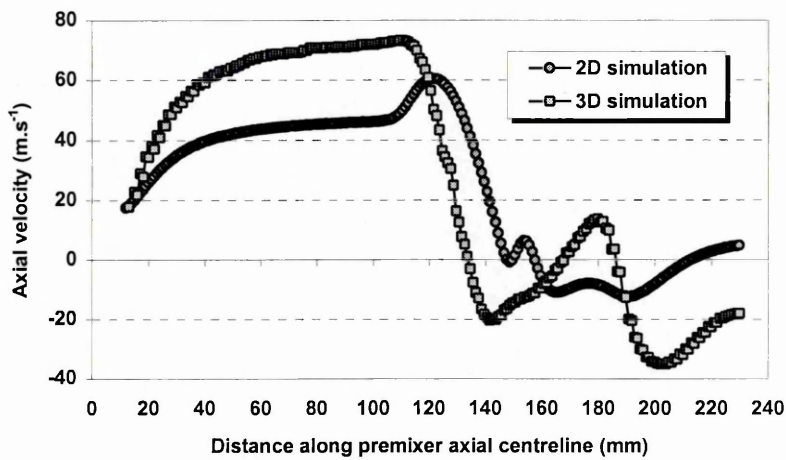


Figure 7.32 Axial velocity along the premixer centreline

Moreover, the recirculation in the 2D case can be seen between about 160 to 210 mm distance which corresponds almost to the exit plane of the duct. Since the recirculation is strongly dependant upon the swirl components of the air flow, a variation in the mass flow split between each channel would yield very different simulation results. Therefore, the computed mass flow through each swirler was checked and are shown next.

	S _{cb} (%)	S ₄₅ (%)	S ₆₀ (%)	S ₃₀ (%)
2D case	4.71	30.70	32.01	32.58
3D case	4.35	31.96	30.89	32.80

Table 7.3 Swirler air mass flow split percentage

These results show very similar air flow distribution for each swirler channel. As a result, the differences in the predictions of the 2D and the 3D are assumed to be related to either the magnitude of the velocities or their profiles. Thus, the velocity profiles at two locations were plotted for both cases. The first plane was 1 mm upstream of the injection point and the second at the throat of the duct. These velocity plots are shown in figures 7.33 to 7.35 and 7.36 to 7.38. For the plane upstream of the injection point the distances are projected along the Y-axis.

With reference to Figure 7.33, it can be seen that the axial velocity profiles agree reasonably well with each other in terms of magnitude. The variation is about 10% and shows slightly higher axial velocity magnitude for the 3D case in the inner channel. As for the middle and the outer channel, the 3D simulation predicts lower magnitudes. The transition between one channel to the other is smoother in the 3D case.

The radial velocity profiles (Figure 7.34) are indeed very similar. The main difference is the smoother transition between the different channels. It is important to notice that the radial velocity reduces from the inner channel towards the outer channel. With the injection taking place in the inner channel, the radial component of the velocity thus acts as an adverse condition to the injection. This would be discussed further in the analysis of the jet breakup.

However, the tangential velocities (Figure 7.35) at the vicinity of injection show similar profiles but with very large variations in the inner and the outer channels. The predicted swirl is much stronger in the 3D case in those channels (almost 50% higher). Since the axial and the radial velocities were found to be in the same order of magnitude, this result suggests that the swirl generated by discrete vanes is more accurate than the axisymmetric flow assumption.

The velocity profiles at the throat of the duct are plotted in Figure 7.36 to 7.38. It can be seen that the axial velocity magnitude is lower in the core of the premixer for the 3D case. The centre-body has a radius of 7 mm after which the profiles become flat in both cases. The radial velocity shows a very large difference across the whole plane of the throat. This at first may appear surprising but the nature of the 3D radial velocity profile is connected to the recirculation. In the 2D case the recirculation is further downstream, thus the axial velocity remains much flatter in nature.

Finally, with reference to Figure 7.38, a similar tangential velocity profile is predicted by both the 2D and the 3D. The positive swirl values at the beginning are due to the counter rotating centre-body swirler. The reduction in the swirl occurs much faster in the 2D case than in the 3D. The latter case shows sharp reductions near 7 mm which corresponds to the centre-body radius. Thus, it can be inferred that the centre-body swirl is also more accurately described by the 3D case.

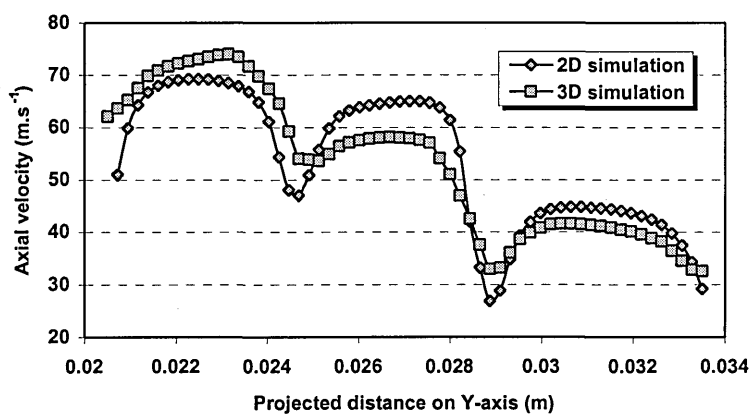


Figure 7.33 Axial velocity profiles of geometry 5
(1 mm upstream of injection plane)

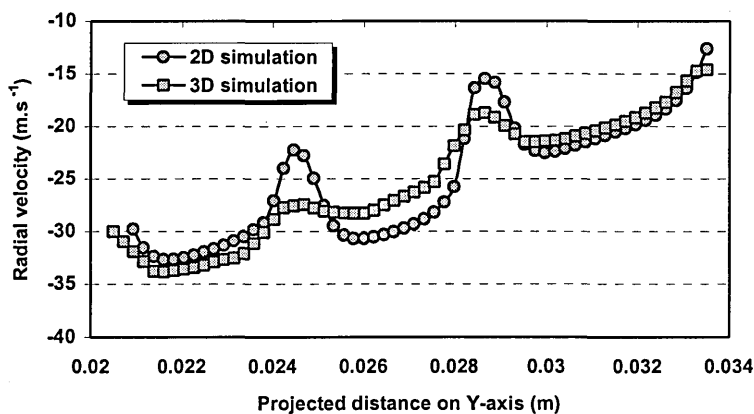


Figure 7.34 Radial velocity profiles of geometry 5
(1 mm upstream of injection plane)

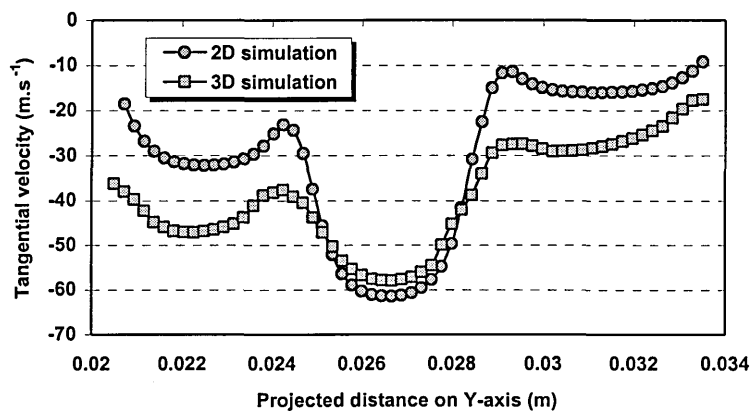


Figure 7.35 Tangential velocity profiles of geometry 5
(1 mm upstream of injection plane)

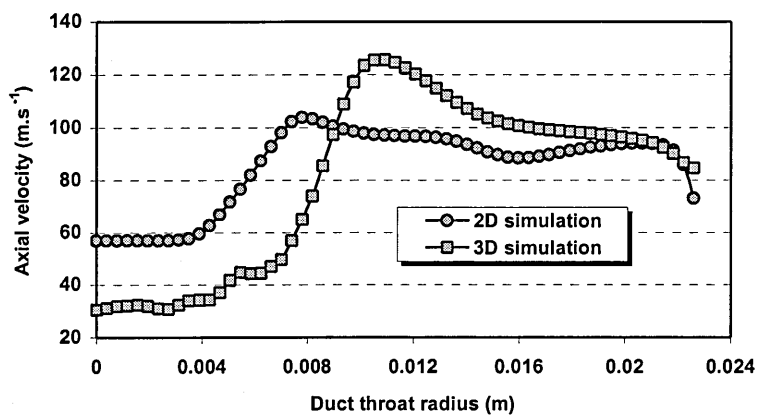


Figure 7.36 Axial velocity profiles of geometry 5 (at the throat of the duct)

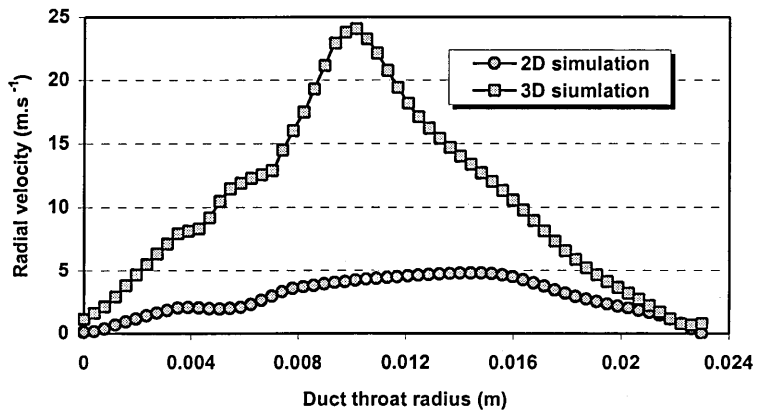


Figure 7.37 Radial velocity profiles of geometry 5 (at the throat of the duct)

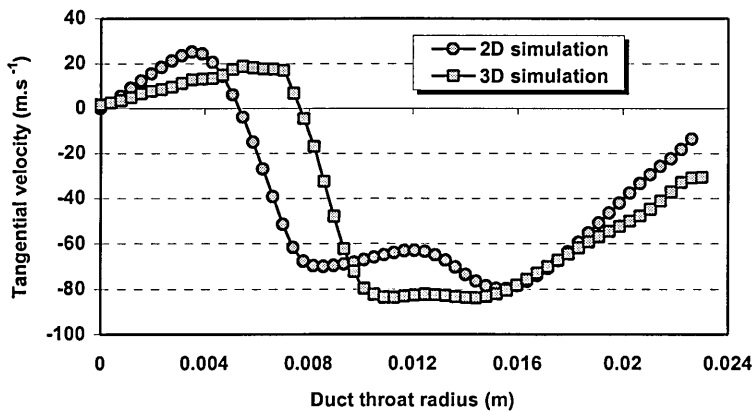


Figure 7.38 Tangential velocity profiles of geometry 5 (at the throat of the duct)

7.6 Fuel jet breakup study

The CFD simulations discussed above provided a qualitative description of the flow field in the premixer. Based on the knowledge of the air flow velocity near the injection point, a simplistic study of the liquid jet breakup was carried out. This was undertaken in an attempt to elucidate the collapse of the jets on the centre-body wall.

7.6.1 Study of jet breakup in subsonic flows

The atomisation, i.e. the process of breaking up a jet into much smaller diameters than the jet, has been the object of extensive research. Although at present the knowledge of the fundamental mechanism of atomisation is far from complete (Lin & Lian, 1990), examples of experimental and theoretical investigations of the break up process are abundant in the literature. For instance, the experimental and the modelling investigations of sprays and the liquid jets were respectively undertaken and reviewed by Faeth *et al.* (1995) and Teng *et al.* (1995).

Others have investigated the trajectory of the liquid jets and have found empirical correlation for the description of the trajectory as a function of flow parameters. For instance, Chen *et al.* (1993) used a Mie scattering technique to investigate jet trajectories up to 60 nozzle diameters downstream. On the basis of their measurements and observations they developed a three parameter exponential function. This function accounted for three different regimes of the spray, namely the liquid column, the ligament and the droplet regimes. The jet penetration trajectory is shown in equation 7.22.

$$\left(\frac{H}{d}\right) = 9.91(\bar{q})^{0.44} \left[1 + 1.06e^{\left(\frac{-x}{0.86d}\right)} \right] \left[1 + 1.67e^{\left(\frac{-x}{4.77d}\right)} \right] \left[1 - e^{\left(\frac{-x}{13.1d}\right)} \right] \quad (7.22)$$

where H is the penetration height, d the nozzle diameter and $\bar{q}$ the liquid-air momentum flux ratio defined as:

$$\bar{q} = \frac{\rho_f V_j^2}{\rho_\infty u_\infty^2} \quad (7.23)$$

where the subscripts f or j and ∞ are respectively the fluid or liquid jet and freestream air properties. ρ is the density of the air or the liquid jet.

The first term which has the shortest characteristic length scale, 0.86 jet diameters, represents the near field or the liquid-core region. The second term, 4.77 jet diameters, corresponds to the intermediate zone of ligaments and finally the longest characteristic length scale, 13.1 jet diameters, represents the far field which is the droplet region.

In a similar study, Wu *et al.* (1997) investigated the near-field structures of spray plumes to characterise the liquid column properties and the breakup mechanisms of liquid jets injected into air crossflows. They used three nozzles with exit diameters of 0.5, 1.0 and 2.0 mm. The injection velocities were varied from 8.8 to 38.5 m.s⁻¹ and the air stream mach numbers were limited to 0.2, 0.3 and 0.4. They concluded that the liquid jet trajectory could be correlated as:

$$\frac{y}{d} = 1.37 \sqrt{\bar{q} \left(\frac{x}{d} \right)} \quad (7.24)$$

where x and y represent the axial and the transverse height of the column. The liquid jet breakup height and distance (subscript b) as shown in Figure 7.39, were found to be:

$$\frac{y_b}{d} = 3.44 \sqrt{\bar{q}} \quad (7.25)$$

$$\frac{x_b}{d} = 8.06 \quad (7.26)$$

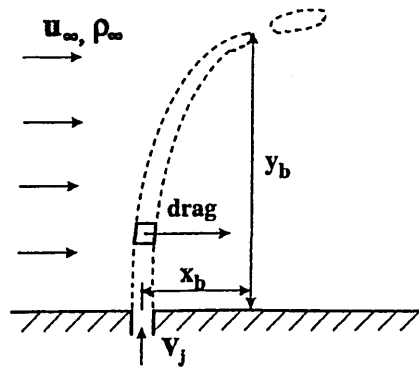


Figure 7.39 Schematic of liquid jet breakup (Wu *et al.*, 1997)

As it can be seen the correlation derived by Chen *et al.* (1993) and Wu *et al.* (1997) were based on a free stream air velocity with an axial component only. However, in the actual LPP premixer, the liquid jet is subject to an axial, radial and tangential velocity components which are turbulent.

Nevertheless, since the present study focuses only on the local breakup properties of the jet, the effect of the radial and the tangential velocities on those parameters are assumed negligible as a first approximation. For the purpose of this study the breakup height, as derived by Wu *et al.* (1997), would be considered as a reasonable approximation of the jet penetration distance.

7.6.2 Boundary conditions

With reference to figure 8.33 and based on the results of the 3D simulation, an average axial velocity of $u_{\infty} = 70 \text{ m.s}^{-1}$ near the injection point was assumed to be adequate. The air density can be calculated from the ideal gas law:

$$p=\rho RT \tag{7.27}$$

which with specific gas constant $R = 0.287 \text{ kJ.kgK}^{-1}$, $T_{\text{air}} = 917 \text{ K}$ and $p = 1.04 \times 10^5 \text{ Pa}$ yields a density of $\rho_{\infty} = 0.395 \text{ kg.m}^{-3}$. In order to determine the liquid jet boundary conditions, the effective flow area ($A_{\text{eff.}}$) of the atomiser needed to be calculated. The flow number in square meters is defined by the following relationship (Lefebvre, 1989):

$$FN=A_{\text{eff.}}=\frac{\text{flow rate (kg.s}^{-1}\text{)}}{\sqrt{\Delta p \text{ (Pa)}}\sqrt{\rho_f \text{ (kg.m}^{-3}\text{)}}} \tag{7.28}$$

The velocity of the jet can be then found using equation 7.29 which relates mass of liquid to the density, velocity of the liquid and the injection effective area:

$$m_L=\rho_L A_{\text{eff.}} v_j \tag{7.29}$$

For an equivalence ratio of $\phi=0.6$ and air mass flow of 60.40 g.s^{-1} the overall fuel flow was $m_L= 2.41 \text{ g.s}^{-1}$. The pressure drop of the injector in the 15 hole and 5 hole configurations were respectively $\Delta p = 7586 \text{ Pa}$ (1.1 psi) and $\Delta p = 37885 \text{ Pa}$ (5.49 psi).

	$m_L \text{ (g.s}^{-1}\text{)}$	$\Delta p \text{ (Pa)}$	$A_{\text{eff.}} \text{ (m}^2\text{)}$	$V_j \text{ (m.s}^{-1}\text{)}$	$\bar{q}$
15 hole	2.41	7586	9.907×10^{-7}	3.118	4.311
5 hole	2.41	37885	4.443×10^{-7}	6.969	21.535

Table 7.4 Injector liquid-air momentum flux ratio

The momentum flux ratio for each injector was determined and is shown in Table 7.4.

The breakup height, as proposed by Wu *et al.* (1997), could be easily determined from equations 7.25. The breakup length described by the equation 7.26 was then used to determine the height of the liquid jet as proposed by Chen *et al.* (1993). The results are shown in Table 7.5.

	Chen <i>et al.</i>	Wu <i>et al.</i>
15 hole	3.97	2.50
5 hole	8.05	5.59

Table 7.5 Liquid jet breakup height (mm)

It has to be reminded that the above breakup heights were determined by assuming the air flow to be only axial. In operation, the jet is subjected to a strong radial velocity component which may cause a reduction in the actual penetration distance. The magnitude of the radial velocity, with reference to Figure 7.34, is about 34 m.s⁻¹. This is very strong compared with the velocity of the jet which is about 3.2 and 7 m.s⁻¹ depending on the injector. The local radial velocity at the exit of the inner prefilmer can also be seen in Figure 7.30.

The breakup heights by Chen *et al.* were found to be higher than those suggested by Wu *et al.* However, since the investigation of Wu *et al.* sought primarily to address the breakup locations of the jet, it is assumed to be a more accurate description of the actual breakup height. These properties are in agreement with visual observations but could not be captured by the video imaging for evidence, due to lack of optical access.

Given that the inner injection channel has a width of 5 mm, it can be seen that for the original injector configuration the liquid jet is likely to collapse on the centre-body. As a result of the strong adverse radial velocity present near the injection point, the liquid jet is primarily believed to be confined to this inner channel. Although, in the modified configuration (5 hole) the liquid jet could potentially reach the middle channel, in practice it is unlikely to be the case. Despite the fact that some liquid was observed on the wall of the premixer, this could not be directly contributed to the increased jet penetration in the modified configuration. The likely explanation for this observation, is the effect of the swirl on the liquid. Thus, the proportion of the liquid which penetrated further was possibly entrained towards the wall of the duct by centrifugal forces.

7.7 Summary

A 3D and a number of 2D simulations of the RR premixing combustor module were performed for different geometries. Although limited to an isothermal case, i.e. non-combusting and based only on one turbulence model (the two-equation $k-\varepsilon$ model), they have provided insight into the aerodynamics of the duct. The influence of the heat release from the combustion is likely to result in different velocity field in the premixer. However, for the purpose of this study, the overall aerodynamics features were considered to be acceptable in an isothermal case.

It has been found that for the various simulated geometries the location of the recirculation in duct has approximately remained unchanged. This has been established in the divergent section of the duct. The CFD results also showed that the shortening of the prefilers resulted in reduced axial velocities near the throat of the duct. At the same time, base on the experimental observations, this trimming of the prefilers caused the injection liquid jets to collapse on the centre-body. Consequently, the combination of a relatively fuel rich region at the exit of the centre-body and lower axial velocities, promoted a reduced flame stand-off distance whereby the flame front moved gradually upstream until it became attached to the centre-body.

In order to overcome the collapse of the jets on the centre-body the injector was modified to obtain a higher liquid momentum flux and increased jet penetration. Although this objective was achieved it also resulted in the liquid being entrained towards the wall of the duct. This also resulted in poor mixing since the spatial distribution of the fuel was less uniform in a 5 hole injector configuration than in a 15 hole configuration. The breakup height of the liquid jet in a 5 hole injector configuration was found to occur in a zone where the strongest air radial velocities were present. As a result, the penetration of the jets has been limited to the breakup height. In presence of strong radial and axial velocities in the vicinity of the injection point, the liquid jets have been entrained towards the wall of the centre-body. In the 5 hole configuration of the injector, the further penetration and the increased breakup height of the jet has alleviated the collapse of the jets. However, they were found to be entrained towards the wall of the duct. The breakup height in this case corresponds approximately to the throat diameter of the duct. The swirl velocities are also likely to entrain the liquid fuel towards the periphery and the wall of the duct.

The mass flow splits of the geometry 5 in both the 2D and the 3D predict that only about 4.5% of the air flows through the centre-body. By allowing a larger percentage of the air flow through this section it may be possible to push the flame further downstream. However, this is also anticipated to emphasise the hollow toroidal nature of the recirculation. In addition, this will result in a lower mass flow percentage in the main swirling section (for the same combustor pressure drop). Therefore, even lower axial velocities at the periphery of the duct may develop promoting aggravated flame flashback.

Chapter 8

Conclusion

The aim of the present study was to characterise the fuel-air mixture preparation of two realistic low NO_x gas turbine combustor modules for small and large engines. To this end, planar laser fluorescence imaging was chosen as a diagnostic tool to measure fuel concentrations. A fluorescence signal calibration procedure was derived so that some of the results could be quantified. Prior to those measurements, the above modules were designed to operate on an existing atmospheric LPP test rig. The measurements provided quantitative and qualitative information on the fuel vapour placement and qualitative data on the liquid phase for these premixing modules. CFD modelling was also performed to gain further insight into the operational features of each combustor module. The summary and the main findings of this work are summarised in the following paragraphs.

In order to calibrate the fuel-vapour fluorescence signal a vaporiser was designed. Naphthalene, with strong vapour phase fluorescence, was chosen as the fuel marker. It has a boiling point of 217 °C which represents the middle boiling fractions of kerosene. However, to overcome fluorescence interference from the aromatic molecules contained in kerosene, it had to be substituted by Exxsol. The fluorescence signal of naphthalene was calibrated against known conditions of temperature and concentrations of air-fuel mixtures. This calibration was derived for a non-combusting environment where the vapour phase is predominantly present. For the study of the liquid phase, azulene was chosen as the fuel marker. It has a strong fluorescence signal in the liquid phase and has a boiling point of 242 °C. The concentration of azulene was adjusted such that the fluorescence signal would be proportional to the mass of the liquid. Nevertheless, the fluorescence was found to be very sensitive to the temperature. Given the multi-component nature of the fuel, further work is required prior to accounting for the effect of the temperature on the fluorescence signal. Recommendations were made for improving the accuracy of these calibration methods.

With regard to the small engine LPP module, quantitative vapour phase measurements of the local equivalence ratios were undertaken. These measurements, at the exit of the duct, were limited to the upper operating temperatures to minimise the overlap of the liquid phase fluorescence signal. The results showed that the centre of the duct had a richer core and that lower equivalence ratios were present near the periphery. Qualitative liquid phase measurements, over a wide range of temperatures, showed a significant reduction in the fluorescence signal with increased temperature. The liquid phase fluorescence signal was also found to peak around the centre and the axis of the duct. However, at higher temperatures the signal profile across the duct was much flatter due to higher degree of fuel vaporisation. The bulk of the vaporisation thus occurred where liquid fuel was present. The evaporated fuel fraction was estimated to be around 85% for the inlet air temperature of 450 °C. This was based on the assumption that the fuel was essentially in the liquid phase at 219 °C. Although, this a reasonable assumption for azulene, in reality the onset of the fuel evaporation is likely to occur at around 120 to 150 °C for the lighter fractions of Exxsol. As a result, the evaporation rates are believed to be slightly underestimated.

The CFD simulation results predicted similar equivalence ratio profiles but with significantly lower magnitude compared with the experiments. This was expected since the predicted evaporation fractions were also much lower (49.9% at 450 °C). Nevertheless, the bulk of the liquid was predicted to be around the centre of the duct in agreement with experimental measurements. The vapour phase experiments showed that on average about 25% of the signal was contained in an annulus of 15 to 22 mm diameter. On the other hand only 10% of the liquid fluorescence was found in the same region of the duct exit. The simulated liquid droplet dispersion in the duct showed that the droplets injected at the centre of the duct remained near the axis at the exit of the duct. However, those injected at the premixing tube lip reached the prevaporisation duct wall. Consequently, it could be inferred that not only a small proportion of the liquid was reaching the prevaporisation duct but that the fuel remained primarily along the centreline of the duct.

Therefore, it is possible to obtain a higher degree of vaporisation if a larger proportion of the liquid is directed towards the periphery inside the premixing and prevaporising ducts. The latter incorporates a step prior to the exit and is an interesting feature which

contributes to the evaporation of the fuel. Increased evaporation at the periphery of the duct would also result in a more homogeneous mixture at the exit of the duct, with possible improvements in terms of emissions performance. This improvement can be achieved by a small modification to the existing plain-jet airblast atomiser as to obtain a cone angle at the injection point. Alternatively, this could be achieved by integrating a swirler upstream of the injector to promote radial fuel dispersion in the premixing duct.

With respect to the large engine LPP module, the fuel placement inside the premixing duct was investigated for various geometries. The conditions represented realistic operating temperatures but at atmospheric pressure. A semi-quantitative measurement of the local equivalence ratios showed interference from the liquid naphthalene. Consequently, the investigation was carried out under a qualitative form. It was revealed that by progressively shortening the prefilms the flame front was stabilised further upstream. Depending on the geometry, flame flashback was observed and liquid fuel could be observed in the premixing duct. The flame position was captured by high speed video images. These images showed that there was a flickering component of the flame oscillating between the centre-body and the divergent section of the duct where the flame was first expected to stabilise. The second distinctive feature, as a result of prefilmer trimming, was the collapse of the liquid jets on the centre-body wall. This was aggravated when both prefilms were the shortest. It was thus deduced that the liquid momentum flux was insufficient for reasonable jet penetration to be obtained. Therefore, the injector was modified from a 15 hole to 5 hole configuration. The fluorescence images showed that there was no fuel on the centre-body wall, however, liquid could be observed at the beginning of the premixing duct wall. This also resulted in a weak flickering component of the flame near the periphery of the duct. The flame front was stabilised in the divergent section near the exit of the duct.

CFD simulations were performed in order to gather information about the velocity field in the duct and also to study the fuel jet penetration. 2D simulations were carried out for all geometries and showed two interesting features: The position of the recirculation in the premixing duct remained relatively unchanged from the geometry where both prefilms were long to the geometry with the shortest prefilms. Also, these simulations revealed important reduction in the axial velocity field near the centre-body

and the throat of the duct. The collapse of the liquid jets on the centre-body created a rich core, which with the reduction of the axial velocities, enabled the flame to stabilise further upstream. Given the limitation of the axisymmetric assumption in the 2D simulations, the geometry with the shortest prefilers was simulated in 3D. The tangential velocities were found to be higher in the 3D case and as a result the nature of the recirculation was very different relative to the corresponding 2D case. The computed axial velocity upstream of the injection plane was used to study the penetration of the liquid jet for each injector.

Based on a simple analysis, neglecting the effect of the radial and the tangential velocities, a jet breakup height of 2.50 mm and 5.60 mm were estimated for the 15 and the 5 hole injectors. The 3D simulation also predicted the strongest radial velocities near the injection point. Therefore, it was shown that the jet penetration and the negative radial velocities were in direct competition causing the collapse of the jets after their breakup. The magnitude of the radial velocity was much higher than that of the liquid jets. For the injector with increased liquid momentum flux the likelihood of the liquid being transported to the wall of the duct was also confirmed. The injection holes were located at a diameter of 40 mm. The throat of the duct has a diameter of 46 mm. Thus after breakup, even though the breakup height is larger, the fuel is likely to be entrained by the strong axial velocities towards the wall of the duct. The breakup height, for the 5 hole injector, occurs in a region where the radial velocities are much lower. The swirl velocities would also tend to entrain the liquid radially outwards.

It appears that the liquid jet injection, in this conical centre-body configuration, is an “all or nothing” proposition. Indeed, if large number of injection holes are used so that the circumferential fuel distribution is more regular, the liquid jet penetration would be difficult to achieve. Strong radial velocities would also affect this adversely. On the other hand, with fewer injection holes the spatial fuel distribution will be impaired. Depending upon the location of the injection points there would be a relatively restricted radial distance over which the liquid fuel could expand. For instance, in the current design, if the injection diameter is lowered, i.e. the injection takes place further downstream, it would result in a larger radial distance between the injection points and the duct wall. However this would also result in a reduced fuel residence time and

vaporisation. For higher diameters of injection, the fuel would remain essentially at the periphery of the duct with less opportunity for premixing across the duct.

At realistic operating pressures, as opposed to atmospheric, the liquid jet momentum flux would be higher. Even if it is assumed that the 15 hole configuration injector would create sufficient jet penetration at high pressures, it can be anticipated that some or most of the fuel would still be entrained towards the wall of the duct. Ultimately, if the jet penetration is such that the fuel can hit the prevaporising duct, then the bulk of the fuel is likely to remain along the curvature of the duct. This can potentially be dangerous at higher pressures since combined with the boundary layer of the duct, the risk of autoignition would be greater. With increased jet penetration, an increase in the surface breakup of the jet can also be expected. This may promote flame flashback in an annulus region of the duct near the throat, as captured by video imaging at atmospheric pressure.

Therefore, it can be concluded that there are no obvious incentives in the use of a conical centre-body and that a pressure jet atomiser is unlikely to achieve good performance. Ideally, the fuel jets should be injected near the centre of the duct to allow gradual penetration across the duct. This would promote not only mixing but also vaporisation. Consequently, an airblast atomiser, positioned near the centre-body swirler, may result in better mixing and vaporisation. In general, airblast fuel injectors have exhibited superior atomisation and mixing performance compared with pressure jet atomisers (Micklow *et al.*, 1990). It may also be desirable to direct the swirling flow of each channel in an axial direction, prior to contact with the liquid jet column or the atomised fuel, to avoid adverse effects on the liquid fuel dispersion.

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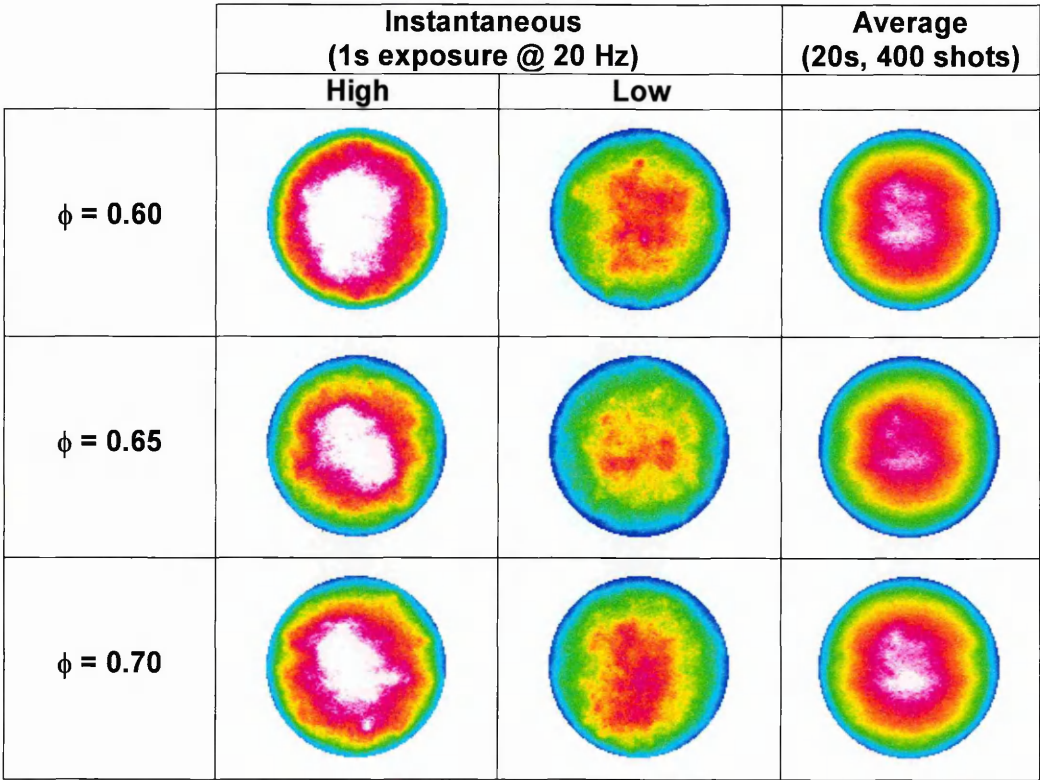
Appendices

General assembly of the Turboméca LPP EV³ module.



Appendix 2

Vapour-phase measurement result of local equivalence ratio on the Turboméca LPP
EV³ duct. The inlet air temperature is 377 °C.



Local equivalence ratio for inlet air temperature $T_{\text{air}} = 377\text{ °C}$

Appendix 3

Correction of local equivalence ratios for mixture temperature variation
(linear correction, $T_{\text{air}} = 333 \text{ }^{\circ}\text{C}$)

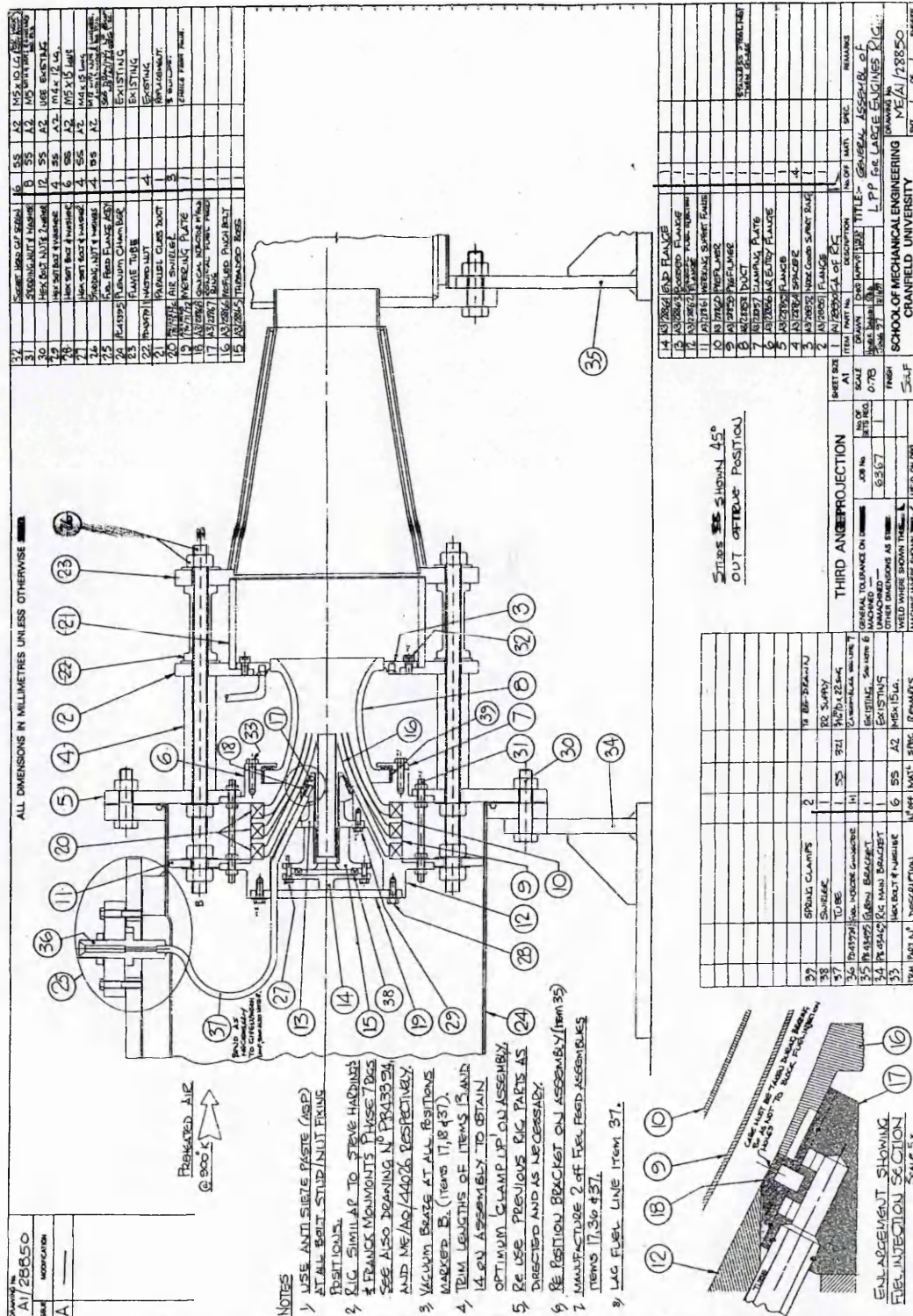
x (mm)	$\phi_{\text{processed}}$	N_{fuel} mol.m ⁻³	T_{mixture} ($^{\circ}\text{C}$)	T_{actual} ($^{\circ}\text{C}$)	Slope processing	Slope actual	N_i (corrected) mol.m ⁻³	$\phi_{\text{corrected}}$
-11.00	0.2877	0.07124	300	250	2265	1887.5	0.0854931	0.31522
-10.12	0.3491	0.08639	300	276	2265	2083.8	0.0938990	0.36362
-9.02	0.4040	0.09991	300	278	2265	2098.9	0.1078149	0.41931
-8.14	0.4560	0.11270	300	299	2265	2257.5	0.1130767	0.45673
-7.04	0.5145	0.12707	300	299	2265	2257.5	0.1274964	0.51532
-6.16	0.5505	0.13591	300	299	2265	2257.5	0.1363603	0.55138
-5.06	0.6068	0.14971	300	296	2265	2234.8	0.1517301	0.61073
-4.18	0.6222	0.15348	300	294	2265	2219.7	0.1566112	0.62829
-3.08	0.6468	0.15950	300	290	2265	2189.5	0.1650015	0.65751
-2.20	0.7091	0.17474	300	286	2265	2159.3	0.1832919	0.72578
-1.10	0.7452	0.18356	300	285	2265	2151.8	0.1932181	0.76405
0.00	0.7402	0.18234	300	285	2265	2151.8	0.1919329	0.75893
1.10	0.6978	0.17198	300	286	2265	2159.3	0.1803947	0.71421
2.20	0.6281	0.15492	300	287	2265	2166.9	0.1619411	0.64176
3.08	0.6445	0.15894	300	290	2265	2189.5	0.1644192	0.65517
4.18	0.6273	0.15473	300	294	2265	2219.7	0.1578855	0.63344
5.06	0.5804	0.14324	300	290	2265	2189.5	0.1481769	0.59000
6.16	0.5091	0.12575	300	288	2265	2174.4	0.1309850	0.51927
7.04	0.4575	0.11307	300	281	2265	2121.6	0.1207137	0.47232
8.14	0.4124	0.10198	300	274	2265	2068.7	0.1116524	0.43114
9.02	0.3903	0.09654	300	255	2265	1925.3	0.1135717	0.42328
10.12	0.3252	0.08050	300	237	2265	1789.4	0.1018928	0.36656
11.00	0.2369	0.05870	300	210	2265	1585.5	0.0838560	0.28543

Appendix 4

Correction of local equivalence ratios for mixture temperature variation
(linear correction, $T_{\text{air}} = 450 \text{ }^{\circ}\text{C}$)

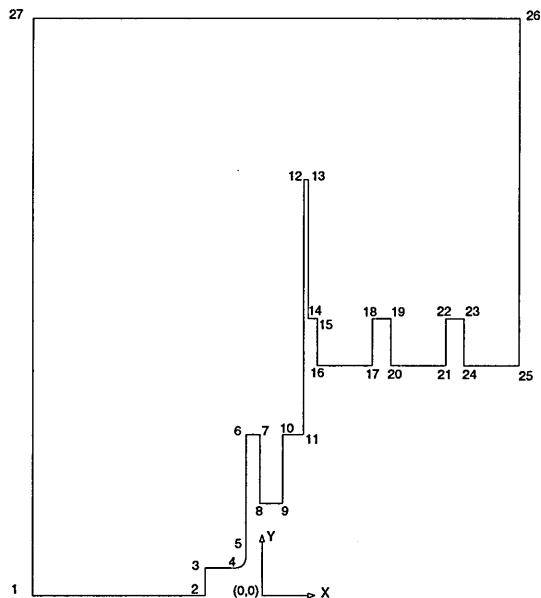
x (mm)	$\phi_{\text{processed}}$	N_{fuel} mol.m ⁻³	T_{mixture} (°C)	T_{actual} (°C)	Slope processing	Slope actual	N_i (corrected) mol.m ⁻³	$\phi_{\text{corrected}}$
-11.00	0.2503	0.05349	420	358	3732	3181.1	0.062756	0.2790
-10.12	0.3382	0.07220	420	400	3732	3554.3	0.075813	0.3599
-9.02	0.3963	0.08455	420	411	3732	3652.0	0.086401	0.4171
-8.14	0.4218	0.08996	420	421	3732	3740.9	0.089749	0.4397
-7.04	0.4946	0.10540	420	421	3732	3740.9	0.105150	0.5157
-6.16	0.5329	0.11351	420	421	3732	3740.9	0.113242	0.5556
-5.06	0.5470	0.11650	420	418	3732	3714.2	0.117054	0.5719
-4.18	0.5578	0.11878	420	415	3732	3687.6	0.120213	0.5849
-3.08	0.5741	0.12223	420	413	3732	3669.8	0.124301	0.6032
-2.20	0.6094	0.12969	420	412	3732	3660.9	0.132210	0.6409
-1.10	0.6582	0.14000	420	409	3732	3634.3	0.143763	0.6943
0.00	0.6445	0.13711	420	408	3732	3625.4	0.141138	0.6805
1.10	0.6425	0.13668	420	409	3732	3634.3	0.140360	0.6777
2.20	0.6255	0.13309	420	410	3732	3643.1	0.136339	0.6591
3.08	0.5904	0.12568	420	409	3732	3634.3	0.129056	0.6227
4.18	0.6022	0.12817	420	408	3732	3625.4	0.131940	0.6358
5.06	0.5789	0.12324	420	405	3732	3598.7	0.127809	0.6130
6.16	0.5309	0.11309	420	400	3732	3554.3	0.118743	0.5650
7.04	0.4937	0.10521	420	393	3732	3492.1	0.112438	0.5292
8.14	0.4631	0.09872	420	382	3732	3394.3	0.108545	0.5023
9.02	0.4359	0.09296	420	356	3732	3163.3	0.109666	0.4873
10.12	0.3665	0.07822	420	325	3732	2887.9	0.101083	0.4267
11.00	0.2916	0.06229	420	275	3732	2443.6	0.095131	0.3677

General assembly of the Rolls-Royce LPP test module.



Appendix 6

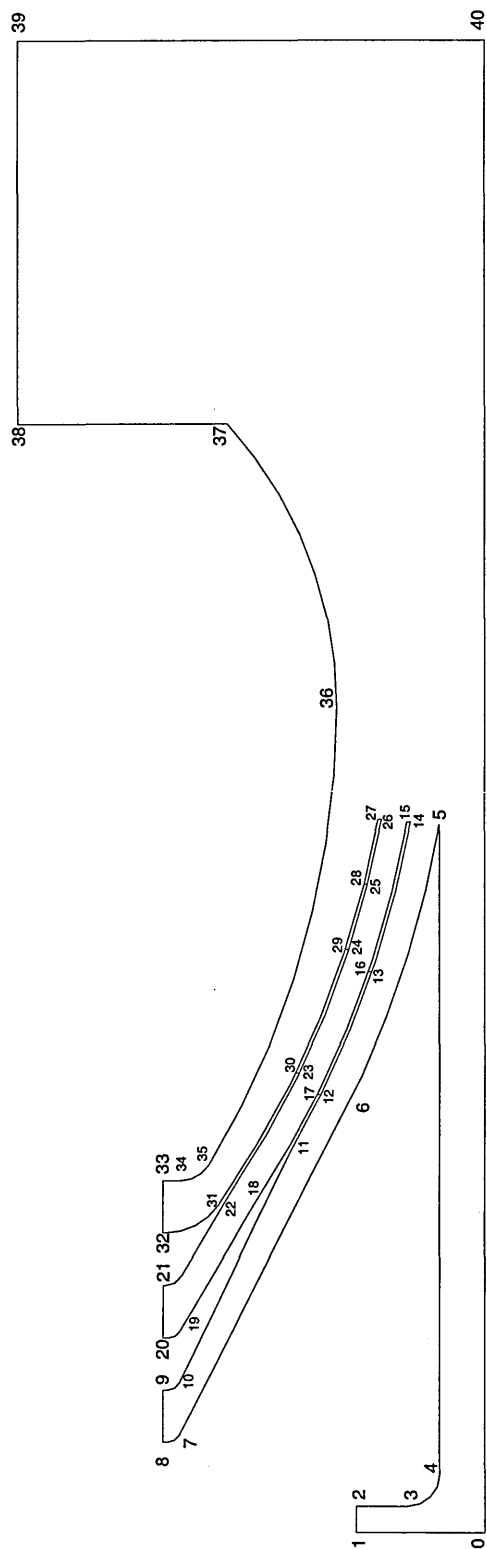
Plenum chamber CFD physical domain (with table of coordinates)



Point	X (mm)	Y (mm)
1	-50.0	0.0
2	-12.0	0.0
3	-12.0	6.0
4	-6.5	6.0
5	-6.5	8.0
6	-6.5	35.0
7	-1.0	35.0
8	-1.0	25.0
9	5.0	25.0
10	5.0	35.0
11	9.0	35.0
12	9.0	90.0
13	10.0	90.0
14	10.0	60.0
15	12.0	60.0
16	12.0	50.0
17	24.0	50.0
18	24.0	60.0
19	28.0	60.0
20	28.0	50.0
21	40.0	50.0
22	40.0	60.0
23	44.0	60.0
24	44.0	50.0
25	56.0	50.0
26	56.0	125.0
27	-50.0	125.0

Appendix 7

Premixer section CFD physical domain (with table of main coordinates)



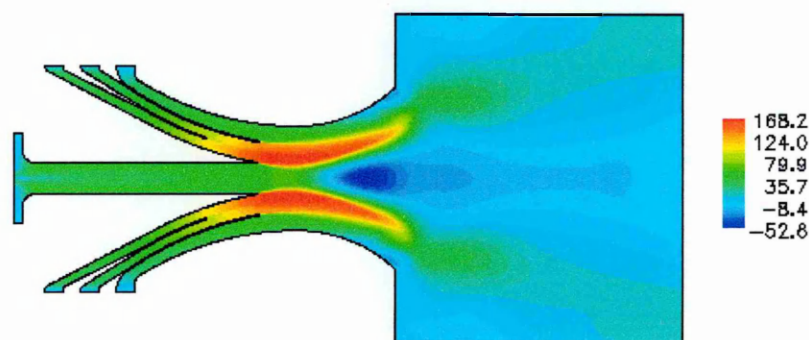
Appendix 7 (continued)

Point	X (mm)	Y (mm)	Curve Centre		
			X (mm)	Y (mm)	Radius
0	0.0	0.0			
1	0.0	20.0			
2	4.0	20.0			
3	4.0	12.0			
4	9.0	7.0			
5	108.78209788	7.0	137.0	165.0	160.50
6	70.083508950	19.115			
7	15.084249790	47.44157283			
8	14.0	50.0			
9	22.0	50.0			
10	23.12325771	47.45215061			
11	58.41774763	30.23787768			
12	67.24	25.46669788	137.0	165.0	156.0
13	86.22861185	17.49316577	137.0	165.0	156.0
14	109.22861185	11.49185689	137.0	165.0	156.0
15	109.22861185	12.0			
16	8622861185	18.02205558	137.0	165.0	155.5
17	67.24	26.02592904	137.0	165.0	155.5
18	52.12900961	34.70354959	137.0	165.0	155.5
19	30.96992385	47.41721095			
20	30.0	50.0			
21	38.0	50.0			
22	52.04847927	39.55882205	137.0	165.0	151.5
23	70.64	28.80675347	137.0	165.0	151.5
24	89.63670341	21.09389125	137.0	165.0	151.5
25	99.64	18.17874677	137.0	165.0	151.5
26	109.63670341	15.99161097	137.0	165.0	151.5
27	109.63670341	16.5			
28	99.64	18.69473557	137.0	165.0	151.0
29	89.63670341	21.62037057	137.0	165.0	151.0
30	70.64	29.63616724	137.0	165.0	151.0
31	50.25531915	41.40242582	137.0	165.0	151.0
32	46.0	50.0			
33	54.0	50.0			
34	54.0	47.20288812			
35	56.38461538	42.94146074			
36	127.0	23.0	127.0	158.0	135.0
37	170.82921400	40.0	127.0	88.0	60.0
38	170.82921400	72.5			
39	230.0	72.5			
40	230.0	0.0			

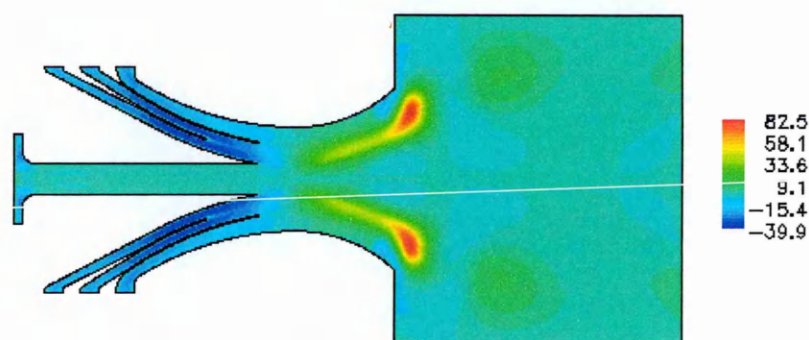
Table of the main coordinates for the premixer CFD domaine

Appendix 8

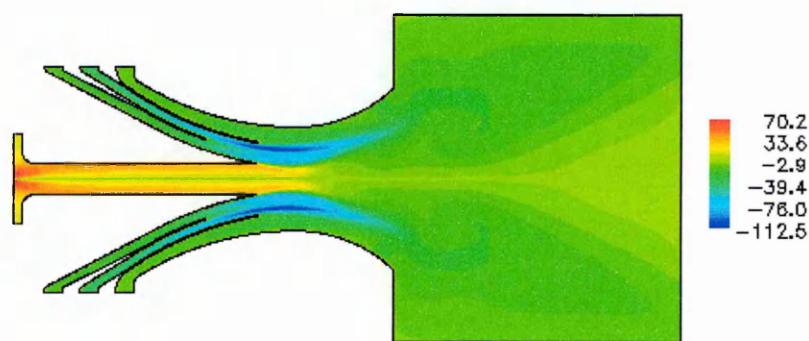
Simulation result of the Rolls-Royce LPP module (Geometry 2)



Axial velocity contours (m.s⁻¹)



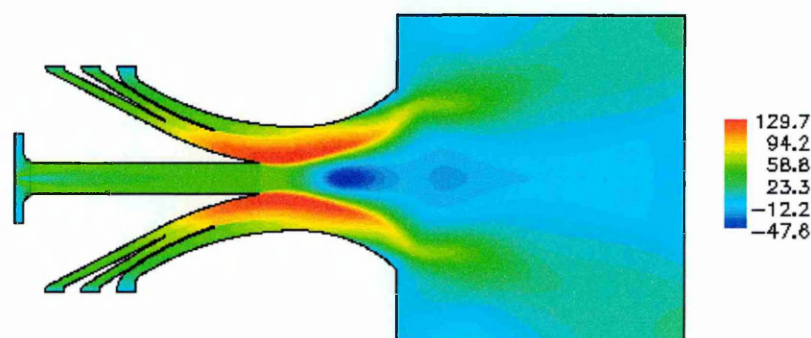
Radial velocity contours (m.s⁻¹)



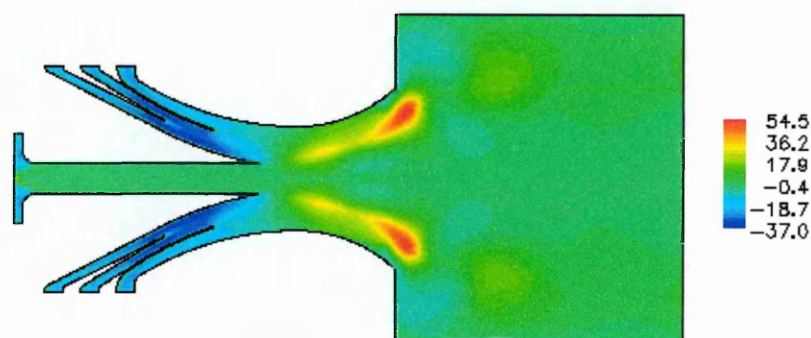
Tangential velocity contours (m.s⁻¹)

Appendix 9

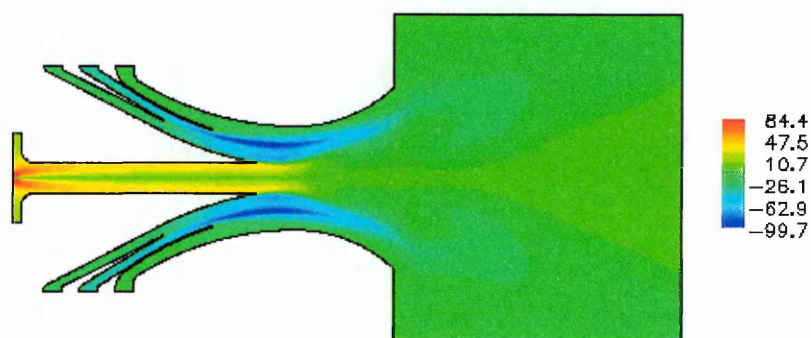
Simulation result of the Rolls-Royce LPP module (Geometry 4)



Axial velocity contours (m.s⁻¹)



Radial velocity contours (m.s⁻¹)



Tangential velocity contours (m.s⁻¹)