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1995

VECTOR-SCALAR IMAGING IN COMBUSTION USING
PIV AND LIF

SCHOOL OF MECHANICAL ENGINEERING

PhD THESIS

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PhD THESIS

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N FARRUGIA

Vector-scalar imaging in combustion using PIV and LIF

Supervisor: Prof. D. A. Greenhalgh.

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for the degree of Doctor of Philosophy.

Abstract.

The effect of turbulent flow-fields on a premixed flame-front has been of considerable interest in the field of combustion research. Modern laser diagnostics allow the measurement of important parameters such as species concentration, temperature and flow velocity with an accuracy, resolution and rate of data acquisition that has not been available with physical probes. The ability to simultaneously gather data over a two or three-dimensional region permits powerful digital analysis of the fundamentals of combusting systems.

The aim of this project was to demonstrate the possibility of combining two-dimensional species concentration and velocity measurement techniques, in order to investigate the interaction of a turbulent flow-field at a premixed flame-front.

Digital Particle Image Velocimetry was investigated as a diagnostic for making velocity measurements in turbulent combustion environments. The standard monochromatic two-pulse technique produces a 180° ambiguity in the direction of each velocity vector. In order to resolve the velocity direction directly, a feature that would be important in combustion studies, a novel variation of PIV was developed. Three Pulse Digital PIV used three unequally spaced monochromatic laser pulses to code the flow direction into the images. A triple-correlation function extracted the correct flow direction and resulted in less vector drop-out, since noise correlations were greatly reduced. A complete analysis software package was written to extract the velocity information from both two and three pulse digital PIV images. The technique was tested on various cold flow, demonstrating its ability to resolve the flow direction.

Planar Laser Induced Fluorescence was used to measure the concentration of the OH radical in turbulent premixed methane-air flames. Over four hundred experimental images were obtained and corrected for systematic errors. Fractal analysis of the flame-fronts in these images was used to extract the inner cut-off values, the smallest scale of wrinkling. The inner cut-off distributions were invariant with stoichiometry and maturity of flame. The maximum OH fluorescence signal at each point along a flame-front was used to give a measure of the local mass burning rate. Correlation of the reaction rate with flame curvature class revealed that convex regions had enhanced burning rates, while concave regions had suppressed burning rates.

The two laser diagnostic techniques were combined in an experimental investigation of a triple flame in a counterflow burner. Joint PLIF-velocity and joint OH-velocity images were generated, demonstrating the possibility of using the combination of PLIF and DPIV to study flame-turbulence interactions in premixed combustion.

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Nomenclature.

CCD	Charge coupled device.
CH	Methylidyne radical.
CLIPS	Cranfield Laser Image Processing System.
c.w.	continuous wave.
DPIV	Digital Particle Image Velocimetry.
FFT	Fast Fourier Transform.
LDA	Laser Doppler Anemometry.
LDV	Laser Doppler Velocimetry.
LIF	Laser Induced Fluorescence.
LSI	Laser Sheet Illumination.
LSV	Laser Speckle Velocimetry.
Nd:YAG	Neodymium-Yttrium-Aluminium-Garnet.
OH	Hydroxyl radical.
PDA	Phase Doppler Anemometry.
PIV	Particle Image Velocimetry.
PLIF	Planar Laser Induced Fluorescence.
PLV	Pulsed Laser Velocimetry.
PTV	Particle Tracking Velocimetry.
SHG	Second Harmonic Generator.
XeCl	Xenon Chloride.

Chapter 1.

Introduction.

Study of the fundamentals of combustion can potentially lead to better informed design of combustion devices. There has been a continuous drive for optimisation of devices such as internal combustion engines and gas turbines, with the aim of producing higher power output for the use of less fuel. In recent years, more stringent pollution legislation has added to the requirement for efficient burning that produces low levels of pollutants, such as carbon dioxide, carbon monoxide, nitrogen oxides, sulphur oxides and unburnt hydrocarbons. The design process has moved towards the requirement for a more detailed knowledge of the combustion process, particularly the case of premixed combustion in a highly turbulent environment.

Combustion models are expected to figure prominently in future design processes. Such models inevitably require experimental data for validation. At a relatively early stage of the development of such models, and of combustion theories in general, the required validation data will be of a more fundamental nature.

In addition to attempting to optimise the burning of fuel, there are other situations where the burning process might need to be suppressed. For example, one important concern of the sponsor (Shell Research Ltd.) has been the behaviour of ignited clouds of accidental vapour emissions. In the hypothetical case of a methane cloud igniting on an off-shore platform, the flames would encounter obstacles, such as the structure of the platform, leading to turbulent premixed or partially premixed combustion. If the arrangement of these pipes and girders caused acceleration of the flames to explosion, the safety repercussions would be serious.

Important quantities in combustion which would be useful to measure include temperature, velocity of the turbulent flowfield and the concentration of species such as the fuel, oxidant, products and intermediates, notably the OH and CH radicals. These radicals occur at the flame-front and can provide reaction rate information (Stårner et al., 1992).

Previous measurement techniques have relied on the insertion of a physical probe into the application, for example a thermocouple to measure temperature or a pitot probe

to measure flow velocity. These devices can provide useful data, but they have certain inherent weaknesses. The most important drawback is perturbation of the application. Physical probes must lie in the flowfield, causing interference. They are generally made from metal and thus conduct heat away from the reaction. They can be fragile, particularly in combusting environments. In addition, physical probe measurements can be subject to large uncertainties and are generally made pointwise, with long response times.

The advent of affordable lasers with output over a wide range of wavelengths has led to a new method of making such measurements - *laser diagnostics*. Laser diagnostics permit the non-intrusive, direct measurement of important properties, with spatial and temporal resolutions far higher than those available from physical probe techniques.

Lasers produce intense coherent light of well defined wavelength over a very short time period (down to 10^{-12} s). These properties allow the generation of high signal strengths of scattered light from a precise point at a well-defined time, with the ability to excite individual species, through absorption lines. By forming the laser beam into a sheet or volume, measurements can be made simultaneously throughout a two- or even three-dimensional region.

Modern semiconductor based digital light gathering devices, such as CCD cameras, can capture the scattered laser light - the measurement signal - and store the data digitally, without interference from competing processes, such as flame luminosity.

In premixed combustion, laminar flamelet models calculate the mean reaction rate as the product of the local mean flamelet area per unit volume, the reactant density and the mean laminar flame speed, averaged over the surface of the flamelet (Cant and Bray, 1988; Becker et. al., 1990). The mean laminar flame speed and reactant density will be determined primarily by the initial stoichiometry and the temperature. Thus, measurement of the local mean flamelet area along a flame-front would provide spatially resolved reaction rate data. This can be achieved by measuring the OH radical concentration (Becker et. al., 1990).

Whilst concentration measurements of major species can be made with Raman scattering, Planar Laser Induced Fluorescence (PLIF) is the best technique for providing instantaneous two-dimensional maps of OH concentration, with a high signal level. The technique uses laser light tuned to an optical transition of the species of interest to excite molecules of the species. Subsequent relaxation paths include the emission of fluorescence, which can be captured with a camera. After suitable correction for

systematic errors, the signal strength can be linearly related to the local concentration of the particular species. PLIF has been developed to become a mature technique, so the focus of this project was to apply it to an interesting application in order to provide useful data.

Turbulent premixed flames are subject to flame stretch due to the flowfield at the flame-front (Bradley et. al., 1992b) and curvature effects (Searby and Clavin, 1986), both of which can alter the local mass burning rate. The flame curvature can be determined with Laser Induced Fluorescence (Üngüt et. al., 1993a). The flowfield at the flame-front can be measured using Particle Image Velocimetry (Armstrong et. al., 1992).

Particle Image Velocimetry (PIV) is an ideal tool for producing two-dimensional velocity maps in combustion studies, where the velocity range of interest is 0-50 m/s. Velocity maps can be used to extract local vorticity and strain rates (Driscoll et. al., 1994). Essentially, a flow seeded with small particles is multiply illuminated with a thin laser sheet and the Mie scattered light is imaged orthogonally with a camera. The displacement of the particles during the fixed pulse separation time is used to calculate the local velocity vector.

An important consideration in attempting to measure the flow-fields encountered in turbulent premixed combustion is the directional ambiguity inherent in the basic PIV technique, i.e. there is a 180° uncertainty in the direction of the velocity, due to the inability to distinguish seed particle images from each laser pulse. The project concentrated on development of a novel variation of PIV that can provide the flow direction unambiguously.

The ability to simultaneously measure flame-front geometry, OH (or CH) concentration, flame-front velocity and temperature over a three-dimensional region would provide a significant proportion of the data required to understand turbulent premixed flames. Measurement of fuel, oxidant and reactant distributions would add fine detail.

A less complete, though still ambitious strategy would combine simultaneous measurement of the flame-front flowfield and geometry with OH concentration over a two-dimensional region. This would allow the variation of reaction rate along a flame-front to be measured and correlated against curvature and turbulent strain effects. The aim of the work reported in this thesis was to investigate making such simultaneous vector and scalar measurements of turbulent premixed flames in two dimensions. As part of the investigation, a novel variation of Digital Particle Image Velocimetry (DPIV) was

developed and a series of PLIF measurements of OH concentration in a highly turbulent premixed flame were made.

Chapter 2 provides the background for the choice of PIV for making velocity measurements. Physical methods and pointwise and two-dimensional laser diagnostic techniques are described, including many variations of PIV. Detail of experimental and analytical procedures common to PIV are covered.

Chapter 3 describes an investigation into the implementation of PIV. A computer based simulation was used to establish likely optimum parameters and to test an analysis algorithm, written as part of the project. The technique was applied to uniform and non-uniform flows, illustrating the usefulness of PIV and the significance of directional ambiguity.

In Chapter 4, the development of a novel variation of PIV is described. A third, non-equally spaced laser pulse was used to resolve the direction of flow and reduce the likelihood of vector drop-out due to noise correlations. The direction of flow must be known unambiguously when measuring a rapidly fluctuating velocity field, which would be found in the vicinity of turbulent premixed flames. The development of the analysis algorithm, a significant part of the project, is described in some detail.

Chapter 5 includes a discussion of premixed flames and the application of fractal analysis to wrinkled flame-fronts. The value of measuring OH radical concentrations is described, in terms of marking the flame-front and giving a measure of the local mass burning rate. The theory of PLIF and its application to OH measurements is covered.

The OH-PLIF technique was applied in an experimental investigation of highly turbulent atmospheric methane-air flames, described in Chapter 6. This application was ideal for measuring the concentration of OH in flames experiencing flame-front strain. By determining the flame-front geometry, the scale of wrinkling could be extracted. The effect of flame curvature on the local reaction rate was investigated.

Chapter 7 describes the background to making joint vector-scalar measurements. An experimental investigation into the application of simultaneous laser diagnostics of flow and species concentration applied PLIF and PIV to a counterflow burner. A discussion of potential improvements to the implementation is included.

Chapter 8 summarises the main achievements and conclusions of this project and includes a discussion of areas where the work could be extended.

Chapter 2.

Flow velocity measurement techniques : PIV.

2.1 Introduction.

Velocity is one of the most important properties of a flow; it characterises the structures in turbulent flows (Bradshaw, 1978), determines mass transport and is an important influence on combustion processes (Kuo, 1986). In flames, the reactant flow-field determines the residence time and is thus crucial to the combustion. Knowledge of the velocity field could allow tracking of the chemical history of individual fluid elements (Libby and Williams, 1994). In the case of liquid fuel airblast atomizers, used in industrial and aeronautical gas turbines, the distribution of the vaporised fuel is determined to a large degree by the relative velocities of the liquid fuel and the air passing through the atomizer. The effect of the external flow-field on the behaviour of a flame, the focus of this thesis, requires knowledge of strain rates at the flame-front.

This chapter describes various techniques for measuring flow velocity. Physical probes are unsuitable for measuring rapidly fluctuating turbulent velocities. Laser Doppler Velocimetry (LDV) can provide pointwise velocity distributions in turbulent flow-fields. However, two-dimensional laser techniques can produce instantaneous full-field velocity maps, measuring the flow structure "frozen in time". This can lead to the calculation of the flow vorticity and strain rates (Driscoll et. al., 1994). Large data sets can be acquired in a relatively short time period, permitting statistical analysis of flow fields to a detail and accuracy not previously possible. The most commonly used two-dimensional technique has been Particle Image Velocimetry (PIV). This technique is described in detail; its theory, variations, experimental requirements and analysis procedures.

This chapter lays the background for Chapter 3, which describes an investigation of the implementation of PIV and Chapter 4, which describes the development of a novel variation with applicability to combusting flows.

2.2 Velocity measurement techniques.

2.2.1 Physical probes.

Traditional velocity measurement techniques involve the insertion of a probe into the flow, to obtain a single or multi component velocity measurement at one position in space. To make measurements at multiple points, the device must be translated, or an array of probes must be used.

2.2.1.1 Disadvantages of physical probes.

All mechanical methods have the inherent problem that the insertion of a probe will perturb the flow being measured. A three-dimensional array of probes would be likely to cause significant errors in the measurements. The devices can also be prone to mechanical failure, e.g. blocking of a pitot probe, which results in high maintenance requirements. It can be difficult to use them in harsh environments, for example, a combusting flow. The measurements rely on secondary characteristics, e.g. pressure differences or heat transfer, rather than a direct measure of displacement over a known time period.

2.2.1.2 Pitot probe.

A standard mechanical device for measuring a flow velocity is a pitot probe (Bryer and Pankhurst, 1971). This is an open ended tube aligned parallel to the flow, with the open end facing the stream and the other end connected to a manometer. The manometer will measure the total pressure P_t , related to the static pressure P for small Mach numbers by :

$$P_t - P = \frac{\rho U^2}{2} \quad (2.1)$$

where ρ is the fluid density and U is the velocity component. The use of a multi-hole probe allows the direction of the velocity to be determined. A pitot probe can measure velocities to an accuracy of 1%, with a spatial resolution of ~ 1 mm and a temporal resolution of ~ 5 s. An array of probes would allow measurements to be made at many points simultaneously.

A pitot probe is simple and reliable for providing velocity measurements in relatively complicated flows. However, it cannot resolve rapidly fluctuating variations in velocity, which are commonly found in combustion applications. Pitot probes inevitably perturb the flow being measured and when there are temperature variations, such as in combustion applications, the value of the density will not be known without a calibrating thermocouple.

2.2.1.3 Hot-wire anemometry.

Hot-wire (hot-film) anemometry (Champagne et. al., 1967) utilises the convective heat transfer from a heated sensor to the surrounding fluid to measure the flow velocity. The signal is compared with a calibration. Such a device will give some improvement in spatial resolution, compared with a pitot probe. The temporal resolution is greatly increased; the frequency response can be up to 10 kHz. This makes hot-wire anemometry much more useful for measuring fluctuating (turbulent) velocity fields.

The extremely fine measurement wires cause much less perturbation of the flow than pitot probes, though the support arms may contribute to perturbation. The wires are very fragile and therefore difficult to use in harsh environments such as combustion applications. Large temperature variations affect the accuracy of the calibration, though a thermocouple may be used to monitor the temperature. A straight hot-wire is sensitive to the velocity component parallel to the supports, but does not measure the instantaneous velocity direction explicitly. This makes it unsuitable for detailed investigation of interactions between flame-fronts and turbulent flows.

2.2.2 Non-intrusive techniques - laser diagnostics.

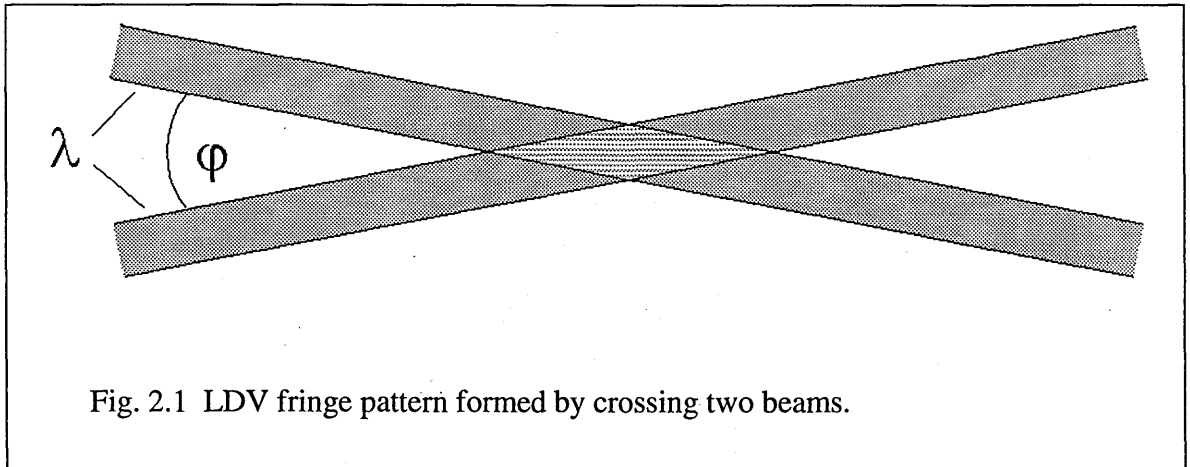
Laser diagnostics can overcome the major drawbacks of physical probes. They are non-intrusive, that is they do not perturb the flow being measured. The equipment is

remote from the flow, so measurements can be made in harsh environments without damaging the measuring devices.

The principals on which they work are generally more complicated, and care must be taken in considering processes that will affect the measurement signal, e.g. alignment, beam steering. Most methods involve introducing seed particles, on the assumption that they will follow the flow, while all methods require optical access to the application, both for the laser beams and for the signal gathering device.

2.2.2.1 Laser Doppler Velocimetry.

Laser Doppler Velocimetry (LDV), or Laser Doppler Anemometry (LDA) is a well established, widely used technique for point-wise velocity measurement. It was pioneered by Yeh and Cummins (1964) and is described in great detail by Durst et. al. (1981). A laser beam, typically from a He-Ne or argon-ion laser, is split in two. The beams of wavelength λ are crossed at an angle ϕ and focused to form a measurement volume at the waists, containing an interference pattern, shown in Fig. 2.1.



The flow is seeded with small particles, that are assumed to follow the flow, and when these particles cross the interference pattern, they scatter intensity modulated light. The rate of intensity variation, i.e. the Doppler frequency ν_D is proportional to the velocity component U of the particle normal to the fringes :

$$\nu_D = \frac{U}{\lambda^*} \quad (2.2)$$

where λ^* is the fringe spacing :

$$\lambda^* = \frac{\lambda}{2 \sin \phi} \quad (2.3)$$

A Bragg cell can be used to introduce a fixed frequency difference between the two laser beams, which will cause the fringe pattern to be non-stationary. The Doppler shift will add to or subtract from this shift. As long as the Bragg shift is higher than the highest negative Doppler shift, the signal processor will be able to distinguish between positive and negative flow directions. A typical system will have a measurement volume of size $50 \mu\text{m} \times 50 \mu\text{m} \times 1 \text{ mm}$ and will be able to make measurements at rates of order 10 kHz. When characterising a flow, the data from 10^5 particles may be gathered over 10 seconds, before either the laser-receiver system, or the flow, is traversed to the next point, typically 1 mm away. LDV is an ideal instrument for making time resolved velocity measurements in a fluctuating flow and has been used extensively in many different applications.

Additional velocity components can be measured by introducing further pairs of laser beams. To keep the signals for each component distinguishable, beams of different wavelengths are used for each component. An argon-ion laser is ideal, as it produces light at 488.0, 514.8 and 476.5 nm, which can be separated with prisms and guided to the transmitting optics through optical fibres.

2.2.2.2 Phase Doppler Anemometry.

Phase Doppler Anemometry (PDA) is an extension to LDA, with the added capability of measuring the size of droplets e.g. in a fuel spray. Using multiple adjacent signal detectors and at certain detection angles, the phase difference in the signals received by different detectors can be related to the droplet diameter (Bachalo, 1980; Wigley, 1994). The application of PDA, rather than LDA, is limited to liquid phase measurements.

2.2.3 Two-dimensional laser diagnostics.

The advantages of making velocity measurements simultaneously over a two-dimensional region are clear. Information about the spatial distribution of features of the flow can be gained. Complete turbulent structures can be seen and their progress can be followed. Velocity field measurements can be used to calculate vorticity and strain rates in order to investigate their effect on flame-fronts (Driscoll et. al., 1994). Early methods of flow imaging produced qualitative "snapshots" of the flow. More recent techniques allow quantitative in-plane velocity measurements to be made.

2.2.3.1 Laser Sheet Illumination.

Laser Sheet Illumination produces qualitative images of flow structure and development. A light sheet is passed through a measurement plane, with the Mie scattered light captured with a photographic or electronic camera, orthogonal to the plane, illustrated in Fig. 2.2.

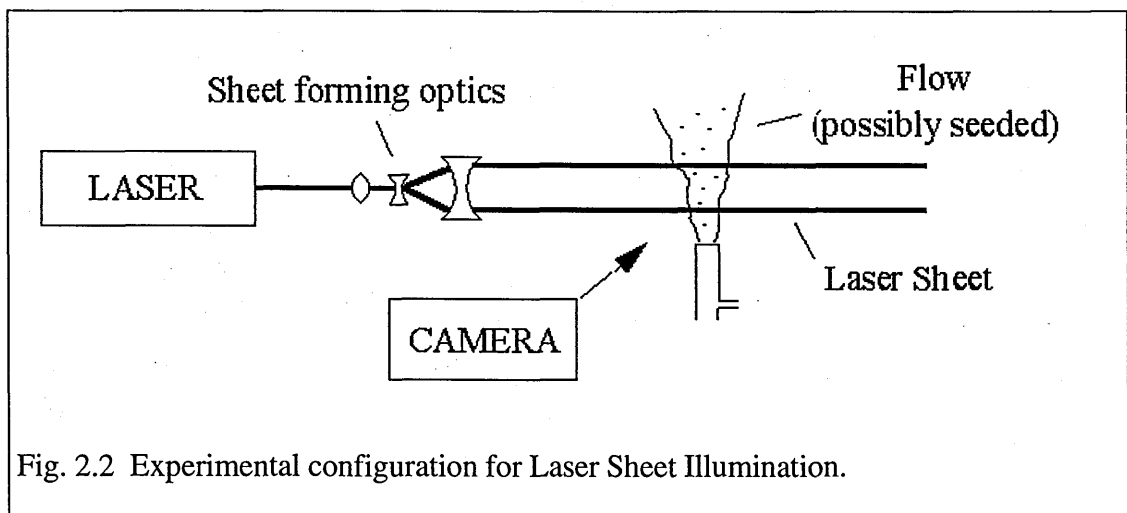


Fig. 2.2 Experimental configuration for Laser Sheet Illumination.

A laser is usually used as a light source, to provide monochromaticity, coherence, low angular divergence and high energy. Typically, it is the sheet thickness ($\sim 200 \mu\text{m}$), not the imaging lens, that defines the depth-of-field of the images. If necessary, the flow is seeded with small particles. The duration of the exposure can be varied until the required flow characteristics can be seen in the image, via the streaks of the scattering particles.

2.2.3.2 Pulsed Light Velocimetry.

Particle Image Velocimetry belongs to a family of quantitative techniques for extracting two dimensional velocity fields, termed Pulsed Light Velocimetry (PLV). Adrian (1991) and Smallwood (1992) give comprehensive reviews of the subject, and are followed to some degree here. There are good PIV-specific reviews by Adrian (1992), Gray (1992) and Buchhave (1994). In each of the PLV techniques, the fluid is multiply-illuminated by a laser sheet. The laser light scattered from seed particles is recorded by some media; the position of each of the seed particles is "frozen" in time, with one image of each seed particle for each laser pulse. The local velocity U at a particular position in the flow is measured by determining the displacement D of seed particles in that region of the flow, over a time Δt :

$$U = \frac{D}{\Delta t} \quad (2.4)$$

By extracting the mean local velocity throughout the field of view, the two-dimensional velocity map of the illuminated region is generated.

There are several ways of detecting particle positions in the flow. Inelastic interaction of the photons with a molecule's energy state results in fluorescence (Gharib et. al., 1985). A photochromic chemical reaction can cause seed molecules to change their optical density (Popovich and Hummel, 1967; Ricka, 1987; Dyson 1991). These methods are not commonly used, principally due to the low signal levels involved. More common methods use elastic Mie scattering of the laser light from particles to indicate the seed position, giving far higher scattering efficiencies.

2.2.3.3 Laser Speckle Velocimetry

At the very high seeding density limit, the images of the particles overlap to create a speckle pattern (Dainty, 1975). This is termed Laser Speckle Velocimetry (LSV) and was the fore-runner of PIV. Dudderar and Simpkins (1977) used a double pulsed, Q-switched ruby laser, with 20 ns pulses and pulse separations of 10-15 ms to form the laser sheet. A Poiseuille flow in a quartz tube was seeded with glycerine and a small

amount of white latex paint. A camera with high resolution film was used to record speckle photographs on a double exposure. Interrogation of regions of the image with a narrow beam of coherent light produced Young's fringe patterns, from which the flow velocity could be deduced. This was the first example of measuring flow velocity in a uniquely defined interior plane, rather than integrating through a volume. Further development of LSV was performed by Barker and Fourney (1977), Grousson and Mallick (1977), Meynart (1983a), Meynart (1983b).

Speckle photographs rely on very high seeding densities, such that particle images overlap throughout the double exposure. Adrian (1984) derived a criterion for creating a speckle pattern, pointing out that in many fluid flow applications, the seeding density will vary significantly, and will often be insufficient to create a speckle pattern.

2.2.3.4 Particle Tracking Velocimetry.

At extremely low seeding densities, when the length of an image set from a particle is small compared with the distance between seed particles, the motion of individual particles can be easily identified by eye. In this limit, the velocity can be inferred by tracking individual particles, termed Particle Tracking Velocimetry (PTV) Although this has not become as common as PIV, many workers have used PTV, for example Adamczyk and Rimai (1988a), Khalighi (1989) and Khalighi and Lee (1989).

2.2.3.5 Particle Image Velocimetry.

With Particle Image Velocimetry (PIV), the particle images do not overlap sufficiently to create a speckle pattern yet there are too many images for the motion of an individual particle to be followed. The common displacement of particles in a small local region is deduced by statistical methods. This has been the most common form of PLV used and was developed by Adrian (1984) and Pickering and Halliwell (1984). When the local velocity in a flow is deduced from the statistics of many seed particles, there is greater confidence in the accuracy of the measurement. This is the advantage that the PIV-correlation methods have over PTV, where a few individual particles are tracked.

2.2.3.6 Directional ambiguity.

The major disadvantage of standard monochromatic, two-pulse PLV techniques is their inherent inability to resolve the sign of the direction of a flow, termed **directional ambiguity**.

In Fig. 2.3, the PIV image contains two images, A and B, of one seed particle. If A came from laser pulse 1 and B from pulse 2, the velocity was $\underline{D}$. If B came from pulse 1 and A from pulse 2, the velocity was $\underline{D}' = -\underline{D}$. For such a pair of images of a seed particle, it is not possible to distinguish which was the actual case.

Where the flow is predominantly in one known direction, directional ambiguity may not be a significant problem. However, in more realistic applications, flow reversals or turbulence result in important directional ambiguities, and methods for automatically resolving the velocity direction would be required when applying PIV to such flows.

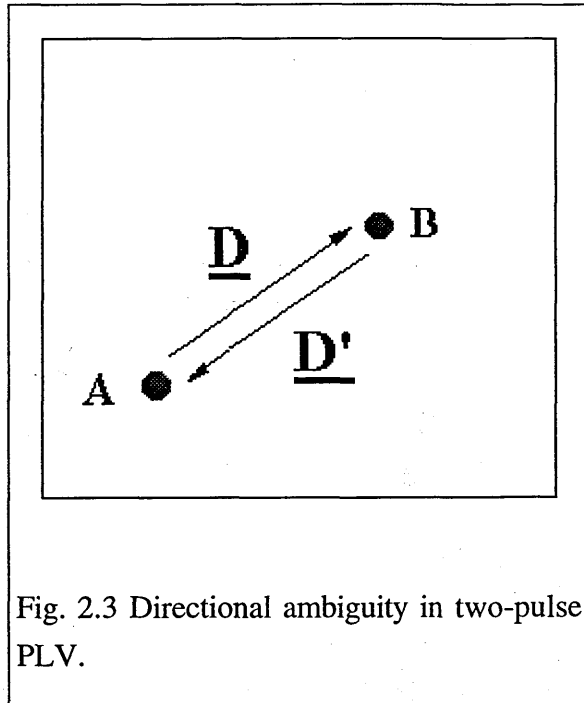


Fig. 2.3 Directional ambiguity in two-pulse PLV.

2.3 Variations of PLV.

There are a variety of different variations of the PLV technique that have been developed in order to resolve the velocity sign and increase the accuracy and bandwidth of the measurements. Some of these are shown in Fig. 2.4 and are described in this section.

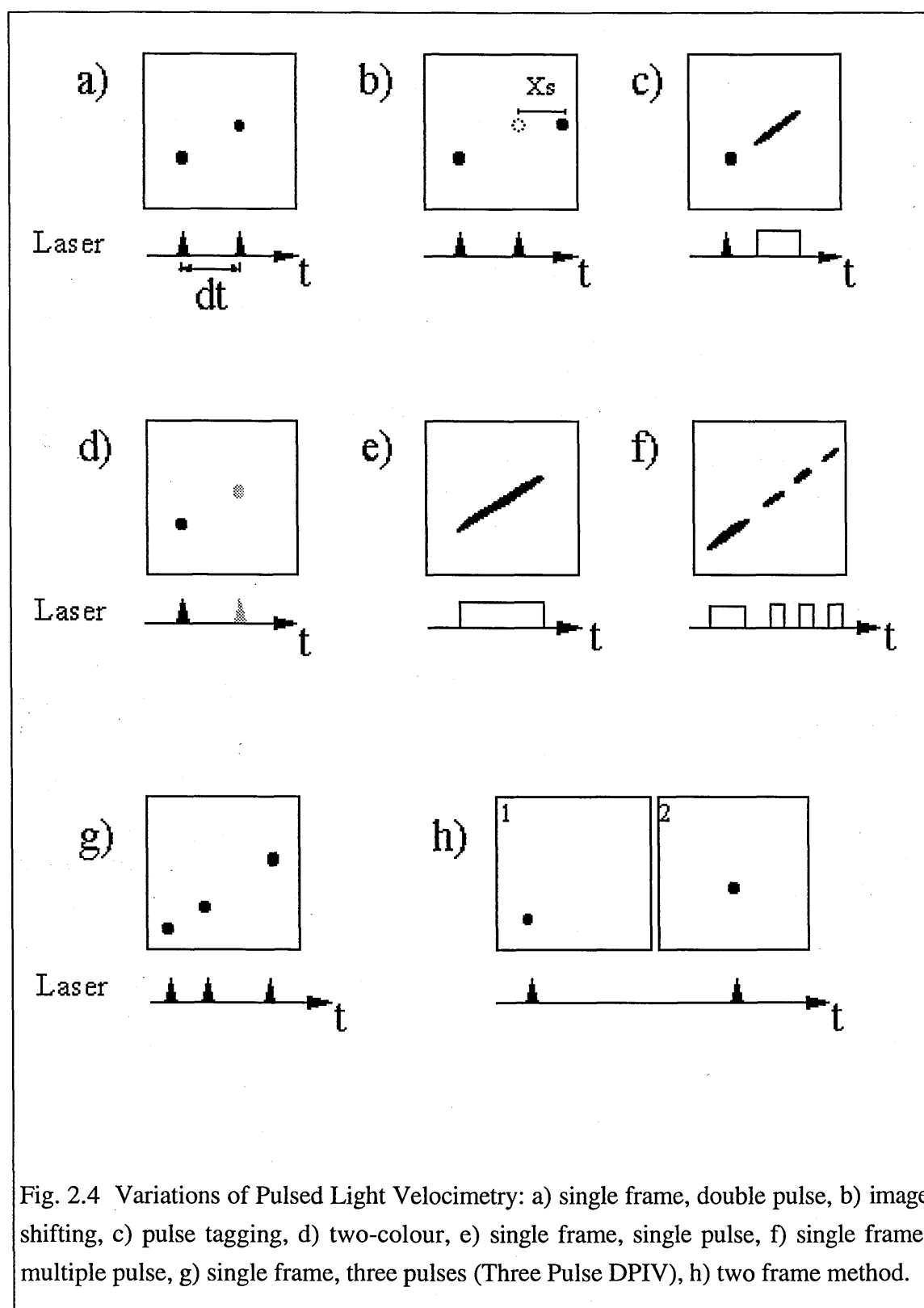


Fig. 2.4 Variations of Pulsed Light Velocimetry: a) single frame, double pulse, b) image shifting, c) pulse tagging, d) two-colour, e) single frame, single pulse, f) single frame, multiple pulse, g) single frame, three pulses (Three Pulse DPIV), h) two frame method.

2.3.1 Single frame, double pulse.

The most commonly used PIV variant has been the original single frame, double pulse, monochromatic PIV (Adrian, 1984; Pickering and Halliwell, 1984), illustrated in Fig. 2.4a. It is the simplest to implement experimentally and analytically. A double-pulsed Nd:YAG laser usually provides the laser light. The image is collected orthogonally with a photographic or CCD camera. After analysis, a velocity vector map is produced, with each velocity possessing a 180° uncertainty. Post-processing algorithms may choose a direction by extrapolation, or a user can manually determine the flow direction. The use of a double-pulsed Nd:YAG laser can limit the measurable velocity range due to the limits of the pulse envelope (see 2.4.5.4). This problem can be avoided by using two single pulsed lasers, synchronising the firing of the pulses with a timing controller unit.

2.3.2 Image shifting.

Image shifting (Adrian, 1986) entails spatially shifting the image on the detector between the first and second exposures, artificially adding a fixed displacement (X_s) between each pair of seed particle images (Fig. 2.4b). The image shift is larger than the largest negative displacement of the flow, such that all displacements in the PIV image are in one direction. The pre-determined "virtual velocity" is subtracted from the vectors in the output velocity map. In effect, image shifting in PIV is analogous to frequency shifting in LDV (see 2.2.2.1). It requires some knowledge of the approximate upper and lower bounds of each velocity component, for example by first performing a non-image shifting experiment. A common problem of all image shifting methods is that they reduce the dynamic range of measurable velocities by the magnitude of the velocity bias.

2.3.2.1 Mechanical image shifting.

Early image shifting experiments used moving mirrors to shift the camera's field of view. Landreth et. al. (1988) used a rotating mirror, placed in front of the photographing lens. The flow field was photographed while the mirror rotated at a constant angular velocity ω_m , resulting in an image shift $X_s = 2M\Delta t(s_o - s_m)\omega_m$, where M is the magnification factor, s_o is the object distance from the camera lens to the flow plane, s_m is the distance from the lens to the mirror. Another variation used a scanning mirror (Lourenco 1986). Moving mirror methods suffer from a systematic defocusing

(Oschwald et. al. 1995). The use of mechanical motion to produce the image shift is subject to limitations on speed due to the dynamics of moving components and on accuracy and consistency. The rotating mirror example was effective only for fluid velocities below about 10 m/s, with a mirror angular velocity variation of $\pm 2\%$.

2.3.2.2 Electro-optical image shifting.

Landreth and Adrian (1988) developed an electro-optical method for image-shifting. The two laser pulses used orthogonally polarised light, either by combining two single-pulsed lasers fired in sequence, or by using a Pockels cell to flip the polarisation of a double-pulsed laser between pulses. A birefringent uniaxial crystal plate was positioned in front of the camera lens, at such an angle that the shift of an image due to the different polarisation of the second laser pulse was equal to the desired X_s . This method gave a more reliable shift than using moving parts. However, the image shift was not uniform over the whole image, the apparatus was somewhat more complex and the method relied on retaining polarisation of the light after side-scatter. This may limit the technique to certain ranges of particle types, particle sizes, angular fields of view and camera apertures.

2.3.2.3 Electronic image shifting.

The ultimate method of image shifting would be to use electronics in the CCD camera to accurately shift the image between exposures. However, such a level of hardware technology would be point towards taking one exposure for each laser pulse with the same camera and performing cross-correlation analysis (see 2.5.2.2).

2.3.3 Image labelling.

Other variations on the single frame, double pulse method involve identifying which of a pair of seed particle images came from which laser pulse, termed image labelling. This allows the seed particle images from each laser pulse to be separated, and the flow direction to be deduced. These methods essentially perform a two frame, cross-correlation experiment, using a single frame.

2.3.3.1 Pulse tagging.

Grant and Liu (1990) used pulse tagging to identify which images of a seed particle came from each laser pulse (Fig. 2.4c). Using chopped argon-ion laser output of two different durations, each seed particle produced a short streak image, preceded by a point image. The algorithm identified pairs of images, deduced the direction of flow, and calculated the velocity, based on the displacement. The technique was visually impressive, though it was effectively a variant of PTV, with low-power c.w. laser output, low seeding density, low measurable velocity range and problems due to streak image blurring.

2.3.3.2 Two colour PIV.

Smallwood et. al. (1985) and Goss et. al. (1991) proposed using two laser pulses of different wavelengths for the two exposures, e.g. a frequency doubled Nd:YAG laser and a Nd:YAG pumped dye laser (Fig. 2.4d). The double exposure could be recorded using colour film or a colour CCD camera. The seed particle images from the first pulse were separated from those in the second using either optical or electronic filters. This method is potentially one of the best for producing directional resolution with a minimum of experimental and analytical complexity and optimum accuracy and consistency. It has been applied in a growing number of cases, e.g. Post et. al. (1994), Stucky et. al. (1994). One possible source of error in the image positions would be differential transmission of the particle images from the different laser pulses, for example through a curved window (Reeves, 1995). Minimising the error by making the laser wavelengths close together would make it more difficult to distinguish the images from each pulse.

2.3.3.3 Other methods.

Other methods that have been proposed for image labelling include recording two separate holograms on one plate (Coupland et. al. 1987) and encoding the point spread function by using adaptive optics at the camera iris (Lawson et. al., 1993; Lawson et. al., 1994; Reeves et. al., 1995).

2.3.4 Single frame, single pulse.

The use of a single frame, with a single long pulse is termed streak photography (Kobayashi and Yoshitake, 1985; Kobayashi et. al., 1985), a variation of PTV (Fig. 2.4e). It can be used to give the two-dimensional velocity of a region, without directional resolution. It suffers from the disadvantages of using a c.w. laser, as well as the problem of automatic analysis of curved streaks and the uncertainty of whether the seed particle entered or left the laser sheet during the pulse duration. It is applicable only to low velocities.

The direction can be resolved by adding a fluorescent tail to one end of the streak by simultaneously firing another laser. There are several different variations, e.g. Busignani et. al. (1994), who used a different colour pulse at each end of the streak.

2.3.5 Single frame, multiple pulse.

The flow direction can be coded into a set of more than two laser pulses (Fig. 2.4f). The most common implementation of this variation is to use the chopped output from a c.w. laser to produce a series of short streaks, with one or more shorter pulses added to distinguish the start of the pulse train (Willis and Deardorf 1974; Khalighi, 1989; Agui and Jiminez, 1987; Braun et. al. 1989). This method requires a low seeding density, and is a variant of PTV.

The minimum number of monochromatic laser pulses required to distinguish the flow direction is three (Farrugia et. al., 1995), provided they are not equally spaced in time (Fig. 2.4g). This variation is not very common, but has many advantages. It forms a significant part of this thesis, and is discussed fully in Chapter 4.

2.3.6 Two frame method.

Collecting the scattered laser light as two separate exposures allows the cross-correlation analysis method to be used (see 2.5.2.2) , giving directional resolution and the ability to measure zero velocities (Fig. 2.4h). This can be implemented with two cameras aligned on the same measurement region or with one camera taking two exposures in the time of the two laser pulses. This can be done with a video camera using "interlaced mode", where the first exposure is collected on the odd lines and the second

exposure is collected on the even lines (Lecordier et. al., 1994; Huang and Fielder, 1994).

Using two cameras will usually involve a post-exposure correction of translation, rotation and magnification of one image. Framing in interlaced mode clearly halves the spatial resolution of each exposure. As camera technology advances, and becomes more affordable, recording separate full-field images on one camera will become the preferred option. Adrian (1991) reported high-speed videos with frame rates up to 80 kHz, equivalent to a pulse spacing of 12.5 μ s, which is of the correct order of magnitude for measuring the velocity ranges common to combustion applications.

2.3.7 Multi frame methods.

Recording many successive frames allows particles to be tracked from frame to frame. This gives the direction and time resolution of the flow velocity. This method is also referred to as Digital Image Velocimetry, when performed using a CCD camera (Cho, 1989; Cho and Park 1990). To increase the accuracy of the measurements, each frame can contain images from multiple laser pulses. This requires a low seeding density for a particle tracking algorithm to be used.

2.3.8 3D-PIV.

It would clearly be advantageous to extend PIV to provide three-dimensional velocity measurements. A review of such methods was given by Hinsch (1994).

An extension of the standard 2D set-up used a thick, intensity graded light sheet (Dinkelacker et. al., 1992). The intensity across the 3 mm thick laser sheet took the form $I(z) = I(0) \exp(-\sigma z)$. Using a low seeding density, chopped c.w. output, particle tracking set-up, tracks of seed particle images showed variations in velocity as the particle moved across the sheet. An algorithm fitted the intensities to the sheet profile to give the most accurate estimate of the third velocity component. It was important to have a non-linear profile and many images of each seed particle. The application of this method to a densely seeded, turbulent flow would be very difficult.

Another 3D method used two parallel light sheets of different colours (Cenedese and Paglialunga, 1989). The third component position of a seed particle was deduced

from the relative intensities of each colour in a particle image. The third velocity component for each particle was found from the rate of change of this position along a particle track. A similar technique was reported by Maas and Gruen (1995).

Some methods use whole-field illumination rather than sheet illumination, recording with two orthogonal cameras (Denger and McBride, 1990; Adamczyk and Rimai, 1988b). To avoid unsolvable ambiguities in matching particles, it was shown that a third camera is necessary (Maas, 1990). These methods require that the depth of field is determined by the imaging lens, rather than sheet thickness and they require more extensive optical access than conventional techniques. Other methods use spectroscopic (Prasad and Adrian, 1993) or holographic techniques (Coupland and Halliwell, 1992).

The rapid development of 3D-PIV techniques since 1988 leads to the expectation that the measurement of three-dimensional velocities in practical flows will eventually be possible.

2.3.9 Doppler global velocimetry.

Doppler global velocimetry (DGV) (Komine et. al., 1991; Meyers, 1995) could potentially provide three component velocity measurements throughout a volume at video frame rates.

In the most common configuration, the flow is seeded with small particles and illuminated by a laser source, tuned to be half way along an iodine absorption line. The scattered light is collected by a camera after passing through an iodine vapour cell. Scattered light from a stationary object or cloud of particles would be attenuated by 50% as it passed through the iodine vapour. If the object or cloud were moving, the attenuation would increase or decrease as the motion caused the frequency of scattered light to be Doppler shifted along the absorption line. Thus, throughout a 2D image, the light intensity would be a measure of the local flow velocity. The use of three detection systems at different angles would allow 3D measurements to be made, following the principle of Maas (1990).

At a relatively early stage of development, the principle limitation of DGV has been the effect of the laser wavelength stability on the accuracy of the technique. The Doppler shift, Δv , of a laser source of frequency v , by a particle moving with speed V is given by :

$$\Delta v = \frac{vV}{c} \quad (2.5)$$

where c is the speed of light. For an argon-ion laser, with wavelength 514.5 nm, the wavelength jitter might be of order 4 MHz, which would give a systematic error of ± 2 m/s to velocity measurements.

2.3.10 Image acquisition - Digital vs photographic PIV.

Conventional PIV experiments use a standard photographic camera to collect the images. These films must then be either scanned by an electronic camera, or analysed by illuminating them with a HeNe laser, to produce Young's fringes (see 2.5.3.1).

The use of a video or CCD camera for Digital Particle Image Velocimetry (DPIV), reported by Willert and Gharib (1991), has many advantages over photographic PIV. Images can be obtained and analysed rapidly so that the experimental conditions such as seeding density and pulse separation can be optimised interactively prior to the collection of a complete dataset of perhaps 100 images. After a roll of photographic PIV images is taken, it may be found that they cannot be analysed, for example if they were over-exposed, or if the seeding level was wrong. Photographic PIV is also limited to the number of exposures on a roll of film.

The DPIV process is entirely electronic from the image acquisition, through storage and analysis to the presentation of results. This removes noise introduced in intermediate steps in wet film processing, allows the analysis to be performed immediately and more quickly and allows more flexibility in the analysis through the use of digital image processing techniques. Cooled CCD cameras have a very large linear dynamic range, with very low readout noise levels.

The disadvantage of DPIV is the total resolution of the CCD array, of order 3000 x 3000 elements in 1995. A standard 35 mm frame of 300 lines per mm Kodak Technical Pan photographic film contains 10500 x 7500 pixels, and a 100 x 125 mm frame of portrait format contains 30000 x 37500 pixels (Adrian, 1991). However, CCD technology has advanced rapidly and the cost of high resolution chips can be expected to fall sharply, eventually leaving DPIV as the clearly preferred method. Commercial DPIV systems became available in 1995 (Dantec, 1995; TSI, 1995).

2.3.11 Choice of technique.

For most workers, the choice of PIV technique would be decided by the requirements of the application, given equipment constraints. In the past most workers would have been content with standard monochromatic, two-pulse photographic PIV. When studying flows with significant turbulence or flow reversals, such as turbulent flames, directional resolution becomes important, so a PIV variant with this feature becomes necessary.

Using a single frame to capture the PIV image is experimentally convenient. The principal advantage of recording multiple frames is that each frame will contain seed particle images from only one laser pulse, allowing cross-correlation analysis (see 2.5.2.2). This can give the flow direction directly and will allow the resolution of zero velocities.

The use of more than two laser pulses permits the resolution of flow direction at a cost of measurable velocity range (bandwidth), whilst two pulse methods with directional resolution require additional hardware.

It is generally desirable to have a robust, low-maintenance, low-labour system. The analysis algorithm will preferably be kept to a minimum complexity, i.e. it should be as fast and as automated as possible, whilst producing accurate velocity maps.

In the work carried out for this thesis, only digital PIV has been used. The work in Chapter 3 investigated the issues of monochromatic two-pulse PIV in more detail. For the work in Chapter 4, a variation using three monochromatic pulses was developed in order to resolve the flow direction.

2.4 Experimental technique.

Generating PIV images is a relatively straightforward matter, but there are several issues that can be important in obtaining images that will give accurate velocity data. The three main components in setting up an experiment are the seeded flow, the laser system and the imaging system.

2.4.1 Seeding.

The seeding of the flow is the key to obtaining good PIV images. First, the appropriate particle type must be chosen. Seed particles must satisfy certain fundamental criteria:

- The particles must scatter sufficient light to be detectable.
- The particle diameter must be smaller than the spatial scales that must be resolved.
- They must follow the smallest temporal and spatial scales of motion resolvable with the rest of the PIV system.
- The particles must survive in the application environment.
- The seeding density must be controllable, such that high image density without speckle may be achieved.
- The particles should be cheap, available in quantities required, and as non-hazardous as possible.

2.4.2 Light scattering capability.

Table 2.1 (from Durst et. al., 1981) compares the light scattering capabilities of different sizes particles, in terms of their scattering cross-sections C_{scat} , the ratio of scattered light to incident light.

<u>Particle size (μm)</u>	<u>Type of particle</u>	<u>Type of scatter</u>	<u>$C_{\text{scat}} (\text{m}^2)$</u>
10^{-3}	Molecules	Rayleigh	10^{-33}
1	Small particles	Mie	10^{-12}
100	Large particles	Mie	10^{-8}

Table 2.1 Elastic scattering cross-sections of different sizes of particles.

The cross-sections from Rayleigh scattering is many orders of magnitude smaller than those obtained from particles of size close to the incident wavelength. In terms of light scattering efficiency, the particles should be as large as possible.

For a particular size, different types of particle scatter with varying efficiency. The best scatter is obtained from solid spheres such as TiO_2 , Al_2O_3 or glass micro-balloons, though water or oil droplets give satisfactory signals. The ability of the seed to survive in a harsh environment, e.g. a flame, may require a more specific material. Witze and Baritaud (1986) compared a variety of seed particles for LDA measurements in engines. ZrF_4 , ZrO_2 , boron nitride and SiO_2 all survived into the flame region. The use of water is attractive as it is the safest seed to use; solid seeds carry dust risks and are sometimes toxic or even carcinogenic.

2.4.3 Resolvable spatial scales.

The particles used to seed a flow must be smaller than the smallest resolvable spatial scales. For PIV experiments, these scales are typically of order $100 \mu\text{m}$, while the turbulence length scale is often in the range $100 \mu\text{m}$ to 1 mm . These criteria place an upper limit on seed particle size of $\sim 100 \mu\text{m}$.

2.4.4 Aerodynamics of seed particles.

When using particles to seed a flow for LDA, PDA, or PIV, the most important requirement is that the seed particles should follow the flow to the smallest scales that

are to be measured. If this is not the case, there can be little confidence in any results obtained.

2.4.4.1 Turbulent fluctuations.

The most important influences on the particle motion are the particle diameter d_p , the particle and fluid densities ρ_p , ρ_f and the viscosity μ . An analysis of the relative motion of particle and fluid (Hinze 1959, Melling 1986) yields the equation:

$$\frac{\pi d_p^3}{6} \rho_p \frac{dU_p}{dt} = -3\pi\mu d_p V + \frac{\pi d_p^3}{6} \rho_f \frac{dU_f}{dt} - \frac{1}{2} \frac{\pi d_p^3}{6} \rho_f \frac{dV}{dt} - \frac{3}{2} d_p^2 \sqrt{\pi\mu\rho_f} \int_{t_0}^t \frac{dV}{d\xi} \frac{d\xi}{\sqrt{t-\xi}} \quad (2.6)$$

where t is the time, U_p and U_f are the instantaneous particle and fluid velocities and $V = U_p - U_f$ is the instantaneous relative velocity.

The first two terms represent the force necessary to accelerate the sphere, and the viscous drag force given by Stokes' law. Acceleration of the fluid leads to a pressure gradient force in the third term. The fourth term is the resistance of an inviscid fluid to acceleration of the sphere. The first, third and fourth terms combined give an accelerating force equivalent to that on a sphere whose mass is increased by half the mass of the displaced fluid. The last term represents the drag force arising from non-steady flow. The equation assumes homogeneity of the turbulence, which can be justified for the small scale motion of a flow, and a small relative velocity between particle and flow. If the relative velocity were not small, the particle would be clearly not suitable, even in a laminar flow.

In all the PIV experiments carried out for this thesis, the seed consisted of liquid or solid particles suspended in a gas. In this case, with density ratio much greater than unity, the particle motion is very closely predicted by considering just the first two terms in Eq. (2.6).

One solution, by Hjelmfelt and Mockros (1966) and Hinze (1959) used U_f and U_p , expressed as Fourier integrals, to give the response of particles of given diameters and densities to different velocity fluctuations. This was expressed in terms of η and β , the

amplitude ratio and phase respectively. One example calculation stated that for TiO_2 particles in air (NTP), with fluctuations of 1 kHz, the criterion of $\eta > 0.99$ held for particle diameters up to 1.3 μm , while for fluctuations of 10 kHz, the maximum diameter was 0.4 μm . These are important considerations for LDA experiments. For the experiments carried out for this thesis, the fluctuation rates were much lower and seed particles in the range 2-5 μm were used. These are commonly accepted as suitable for measuring flow velocities in the range 1-100 m/s with PIV (Weinberg, 1994).

2.4.4.2 Body forces.

There are flows that have no turbulence, but the body of the flow has large variations in velocity, e.g. the counterflow burner in Section 4.3.2. There is still a requirement that the seed particles follow the flow. Considering a centrifugal field, such as a forced vortex flow with zero radial velocity, equating the Stokes' force with the centrifugal force, leads to an equation linking the radial and tangential velocities of the seed particle. For a 1 μm diameter water droplet in air rotating at 9000 rpm, the radial velocity is 0.3 % of the tangential velocity, i.e. the particle follows the flow well (Durst et. al., 1981). The applications considered here did not have rotations of that order of magnitude, so this effect could be neglected.

2.4.4.3 Seeders.

There are several different methods for introducing the seed into the flow. An "atomiser", such as the TSI 9200, entrained liquid (water, oil, suspension of solid particles) into the flow using the Venturi effect, where it was atomised into droplets of size 2-5 μm , depending on the applied pressure. The Palas RBG 1000 solid particle seeder used a rotating brush to pick up a controlled amount of powder from a piston-driven cylindrical reservoir. Pressurised air was forced through the brushes, carrying away the seed particles. The seeded air stream was then introduced into the flow. Another possible method of seeding involves introducing pressurised air through a bed of powder, fluidising it, before carrying away a controlled concentration in order to seed the flow.

2.4.4.4 Seeding density.

Once the seed particle type has been chosen, the correct seeding density must be obtained. If the seeding density is too low, there will not be sufficient correlations for a velocity vector to be derived for each part of the flow. An extreme case occurs when an interrogation region contains the images of two seed particles, i.e. four particle images, illustrated in Fig. 2.5.

With no way to distinguish which particle images are from each seed particle or which came from each laser pulse, there is no way to determine the correct velocity for the region (except from continuity with neighbouring regions) since there are four equally probable displacements: D1, D2, D3 and D4.

If the seeding density is too high, random correlations between images of different seed particles will cause the noise in the correlation function to be too high, again preventing a correct velocity vector from being extracted. (The extreme case of high seeding density occurs when the seed particle images overlap, giving a speckle image.)

Coupland and Pickering (1988) recommended an optimum number of seven seed particles per interrogation volume, whilst Keane and Adrian (1990) recommended a minimum of 15 particles per interrogation region. Both of these numbers were based on Monte-Carlo simulations. Analysis of seeding densities linked to image quality was reported by Guezennec and Kiritsis (1990).

Attaining an appropriate seeding density is the most difficult aspect of performing PIV experiments. In turbulent flows, there are often large variations in seeding density throughout a measurement region. It is particularly difficult to seed uniformly when dealing with combusting flows, since there will be a large change in density from the unburnt to the burnt regions (Armstrong et. al. 1992; Frank et. al., 1996, Ch 7).

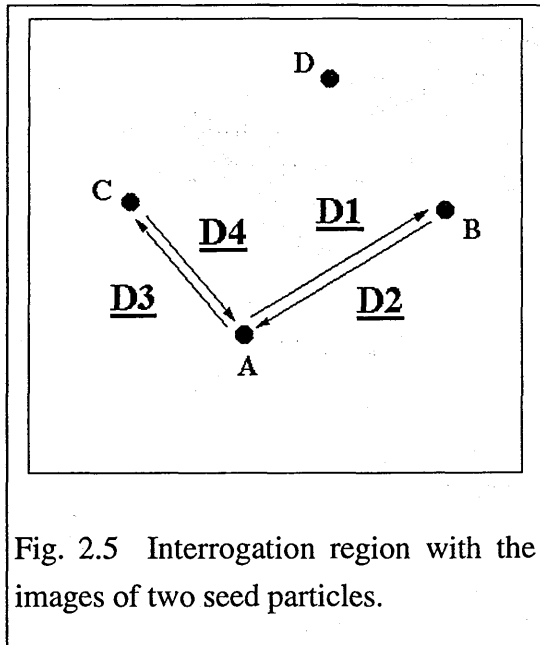


Fig. 2.5 Interrogation region with the images of two seed particles.

2.4.5 Lasers.

Whilst it is possible to use conventional light sources for flow visualisation and velocimetry applications, it is now standard practice to use lasers. These provide an extremely high intensity of monochromatic, coherent light in a very short time period, of order 10^{-8} seconds. This allows the flow to be "frozen in time", without wavelength-dependent variations of scatter throughout an image. A laser beam can be collimated and directed with great precision, allowing the experimentalist to make measurements in well defined regions of a flow.

2.4.5.1 Continuous-wave lasers.

The type of laser used depends on the variation of PLV that is being implemented. For streak photography, or those variants of PTV that use streaks, a continuous-wave laser source will be used, with its output chopped mechanically or electronically. The most common types are the argon-ion laser, or the HeNe laser for low power applications. Continuous-wave lasers provide much lower instantaneous power than pulsed lasers (~ 5 W compared with 2×10^8 W), resulting in much lower scattered light levels. It can be difficult to control the timing of chopped output to pulse lengths of less than 10^{-3} secs, though the use of an electronically gated camera shutter allows control to nanosecond precision. There can be problems with "streaky" images when using long pulse durations (> 100 ns), making it difficult to determine the start and end of each particle trace, though when good measurements are made, the accuracy can be very high.

2.4.5.2 Pulsed lasers.

PIV uses a high seed particle density, with correlation analysis, which requires point particle images in order to minimise signal overlap and maximise spatial resolution. It relies on the collection of Mie scattered light from seed particles showing the instantaneous position of each particle at a given time, i.e. freezing the particles in time. This requirement points to the use of a pulsed laser, where the duration of the laser pulse should be less than the time for a seed particle to travel one diameter.

Using this criterion, for a minimum typical seed particle diameter of $1 \mu\text{m}$, and a maximum typical velocity of 100 m/s , the maximum pulse length would be 10 ns at this extreme. The light source can be of a wide range of wavelengths, though it is more

convenient to use a visible wavelength, particularly if a photographic camera is being used to capture the image.

2.4.5.3 Nd:YAG lasers.

A convenient laser source, and that which is most commonly used, is a frequency doubled Nd:YAG laser. A Nd:YAG laser is a solid state device, and is therefore compact and reliable. The fundamental laser light is at the wavelength 1064 nm, and with the use of a KD*P frequency doubling crystal, and removal of residual infra-red light, a beam of green laser light at 532 nm, with a pulse length of 5-7 ns can be obtained. Typical pulse energies range from 70 mJ to over 900 mJ depending on the laser, though most applications can produce good quality PIV images with a few tens of mJ per pulse.

2.4.5.4 Flashlamp cycle.

An important aspect of the Nd:YAG laser with respect to pulse energy and synchronisation is the flashlamp cycle, illustrated in Fig. 2.6.

The rod of Nd:YAG is excited by an intense white-light flashlamp, which is illuminated for about 350 μ s every 100 ms. The repetition rate of the flashlamp is optimised with consideration of the thermal lensing of the rod and the optics in the laser cavity. The value of 10 Hz is a common one, and has been used in all the experiments performed for this thesis. In order to obtain a

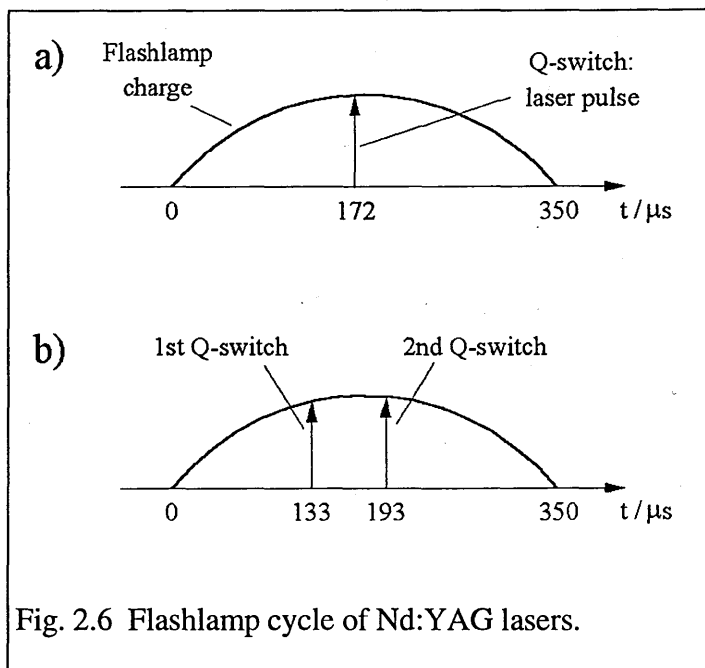


Fig. 2.6 Flashlamp cycle of Nd:YAG lasers.

sharp, well defined laser pulse, the laser cavity is "Q-switched" at a precise point in the flashlamp cycle. Q-switching alters the cavity from a high loss mode, during which a large population inversion can build up, to a low loss mode. This results in a sudden

build up of lasing energy, the magnitude of which will be determined by the time at which the cavity is Q-switched (Q-switch delay) and the flashlamp discharge voltage. For the Continuum lasers used, a Q-switch delay in the range 170-200 μs gave the maximum energy in single pulse mode (Fig. 2.6a).

Two laser pulses could be produced from one laser within one flashlamp cycle, using a double Marx bank. In this mode, the cavity was Q-switched early in the flashlamp cycle, so there was sufficient time for laser energy to build up before the cavity was Q-switched for a second time (Fig. 2.6b). The energy of each pulse might be 80 % of the maximum single pulse energy, depending on pulse separation, which could be in the range 20-200 μs .

2.4.5.5 Sheet characteristics.

There are a number of ways of forming a laser sheet in order to perform laser diagnostics (Long, 1993). The least complex is to use a combination of one spherical and two cylindrical lenses (Fig. 2.7).

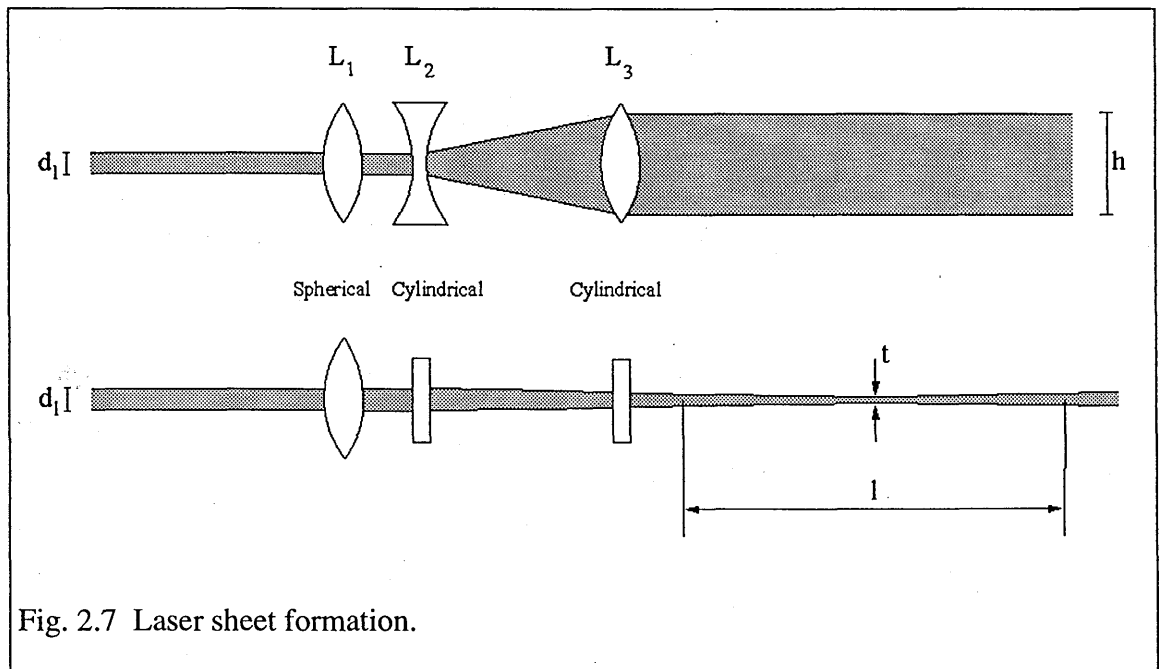


Fig. 2.7 Laser sheet formation.

The spherical lens focuses the beam to a waist, which is usually arranged to be at the centre of the measurement region. The cylindrical lenses form a Galilean telescope (with no focal point) to expand the beam in the other dimension. Such a sheet has a non-uniform intensity profile in both dimensions.

If a uniform sheet is required, one method is to rapidly sweep the beam through the flow with either mechanical or electro-optic beam-steering devices (Lysaght et. al. 1982). Another method uses a multipass optical cell, where the beam is reflected back and forth through the measurement region (Webber et. al. 1979). PIV measurements generally do not require a uniform laser intensity throughout the sheet; the first method was always used throughout the work reported in Chapters 3 and 4.

The dimensions of the laser sheet will be determined by the lenses used to form it, as well as the original beam diameter. Considering the sheet shown in Fig. 2.7, the sheet is formed by a spherical lens, L_1 , focal length f_1 and two cylindrical lenses, L_2 and L_3 , focal lengths f_2 , f_3 . Lens L_1 determines the thickness of the sheet, while L_2 and L_3 determine the height. It is important for the most uniform illumination of the particles possible that the thickness and height of the laser sheet is approximately constant throughout the measurement region, since this determines the laser sheet intensity.

The thickness of a laser sheet t , defined as the diameter at half centre intensity is given by (Buchhave 1994) :

$$t \cong \sqrt{\frac{\ln 2}{2}} \frac{4 f_1 \lambda}{\pi d_1} \quad (2.7)$$

where λ is the wavelength, f_1 is the focal length of the focusing lens, d_1 is the diameter of the laser beam.

The length of the focused sheet l , defined as the points at half maximum intensity is given by (Buchhave 1994) :

$$l \cong \frac{8 \lambda f_1^2}{\pi d_1^2} \quad (2.8)$$

For example, inserting values of $\lambda = 532 \text{ nm}$, $f_1 = 1.5 \text{ m}$, $d_1 = 3 \text{ mm}$, the sheet dimensions would be $t = 200 \text{ } \mu\text{m}$, $l = 338 \text{ mm}$. These values are within the acceptable range for typical applications.

The height of a collimated sheet h will be :

$$h = d_1 \frac{f_3}{f_2} \quad (2.9)$$

though in practice, a non-parallel sheet of more convenient height, related to the specific application, may be used.

The sheet thickness will not affect the image quality in PIV, provided it is thinner than the depth of field (see 2.4.8.4). However, a thicker sheet will reduce the problem of seed particles entering or leaving the sheet between two laser pulses, leaving an unpaired seed particle image. The loss of laser intensity due to thickening the sheet will not normally be a problem, since only relatively small (~ 10 mJ) energies are required to produce good signal levels.

As an example, a seed particle with a velocity component normal to the laser sheet of 1 m/s, with a pulse separation of 100 μ s, will travel 0.1 mm between laser pulses. Thus, if the sheet has a width of 1 mm, there is a 10% chance that any seed particle will produce only one image due to entering or leaving the sheet.

If the sheet thickness is equal to the size of an interrogation region, the effective measurement volume becomes a cube. If the out-of-plane velocity component were equal to the in-plane components, the probability of an unpaired image due to the particle entering or leaving the sheet would be equal to the probability due to the particle entering or leaving the interrogation region. Consequently, there is generally a maximum useful thickness of laser sheet, specific to each individual flow condition and the interrogation region size, beyond which little is gained in terms of minimising unpaired particle images.

2.4.6 Optical Access.

Good optical access is clearly necessary for all laser diagnostics. It must be possible for the laser sheet to enter the application so that it can illuminate the desired measurement region. An exit path for the laser sheet greatly reduces spurious scatter.

The imaging system must be able to gather the light scattered from the measurement region.

In an open application, optical access will usually be straightforward. In a closed application, such as a high pressure combustion rig, windows must be incorporated. Depending on the diagnostic technique and the application, these windows may need tough physical properties to withstand the environment and well-defined optical properties, such as flatness, so that the signal is not significantly perturbed.

In some applications (Berckmüller et. al. 1994), non-flat windows are necessary. These produce problems of distortion of the image and unwanted focusing of the laser sheet, and should be avoided, where possible. A process for correcting such distortions was reported by Reeves (1995).

2.4.7 Camera system.

All the experiments reported in this thesis used a CCD camera to collect images in a digital form. Rather than holding photographic film, such a camera has an integrated circuit, containing potential wells. These can be moved around the CCD array by suitably varying the potential of clock electrodes on the surface of the device. When they are moved, the potential wells carry with them any electronic charge which they may have collected, for example as a result of light falling on the device (Wright Instruments, 1992).

In taking an image, the CCD array is exposed to incident light, via a lens, for a controlled time period, typically 10-20 ms. When the shutter closes, the charge collected at each grid node is digitised, and the array of signals is sent to a controlling PC, which displays the image and stores it to disk.

The cameras used for the DPIV studies were Wright Instruments air-cooled, slow scan CCD cameras, with 15 bit resolution. One camera had an array of 600 x 400 pixels, each of size 25 μm , whilst another had an array of 1340 x 1037 pixels, each of size 6.7 μm . Images could be obtained at a rate of about fifty per minute for the smaller camera, six per minute for the larger, or could be stored on the hard disk of a 486DX2 PC at a rate of fifteen per minute for the smaller camera, one per minute for the larger one. (When subsequently connected to a P90 PC, large area camera images could be stored at a rate of five per minute).

2.4.8 Imaging lens.

Whether a PIV image is to be recorded photographically or digitally, a standard camera lens will normally be used on the camera. The choice of lens will be determined by several factors.

2.4.8.1 Magnification.

The magnification factor, and hence the field of view of the camera and resolution of the PIV system will be decided according to the experimental conditions; the resolution required in comparison with the scale of velocity variation and the fraction of the flow that is to be imaged.

2.4.8.2 Resolving power.

The resolving power of the lens must be considered when assessing the resolution of the PIV system. Theoretical resolving powers of lenses are given in tables (Washer and Gardner, 1953). For example, the resolving power of a 50 mm focal length lens, with aperture settings in the range $f/4$ to $f/11$ is quoted as $12.5\text{ }\mu\text{m}$. In practice, the resolving power of a lens may deviate from the theoretical. One empirical measure is the closeness of parallel lines in the focal plane that can be resolved. This can be easily measured for a particular lens.

2.4.8.3 Light gathering capacity.

The lens must have sufficient light gathering capacity to produce decent signal levels in the PIV image. This will be controlled by the aperture setting. In most cases, light gathering can be sacrificed to improve the focusing by closing down the aperture to, for example, $f/8$.

2.4.8.4 Depth of field.

The depth of field (DF) of a lens is given by Hyzer (1962) as :

$$DF = \frac{u^2}{\frac{f^2}{\Lambda c} - u} \quad (2.10)$$

where u is the distance to the focal plane, f is the lens focal length, Λ is the lens f-number and c is the "circle of confusion", the largest acceptable diameter of the image of a point object which is often taken as $25 \mu\text{m}$.

For the lens used for all the PIV experiments, the values were $f = 60 \text{ mm}$, $\Lambda = 8$, $u = 0.219 \text{ m}$, giving a depth of field of 2.7 mm . Thus, all seed particles in a 1 mm thick sheet would be in focus.

2.4.8.5 Choice of lens.

The most important factor in the choice of lens is the ability to image the required measurement area with the desired magnification, whilst light gathering and resolving capacities can be compromised to some degree.

2.4.9 Image Resolution.

There are two types of spatial resolution associated with PIV:

2.4.9.1 Image resolution.

This is the resolution of the PIV image. It is determined by the physical space imaged by one pixel and the resolving power of the optical system. The large area CCD camera used for most experiments had a pixel size of $6.7 \mu\text{m}$ and often imaged 1:1, giving a pixel resolution of $6.7 \mu\text{m}$. However, the optical system had a resolution more

like the value of $12.5\ \mu\text{m}$ in Section 2.4.8.2, such that many $2\text{-}5\ \mu\text{m}$ sized seed particles gave images extending over 3-4 pixels. The sheet thickness, provided it is in the range $0.1\text{ - }2\ \text{mm}$, will not influence the spatial resolution of the PIV image, since the aim is to extract only the two in-plane components of the flow velocity.

2.4.9.2 Vector Map resolution.

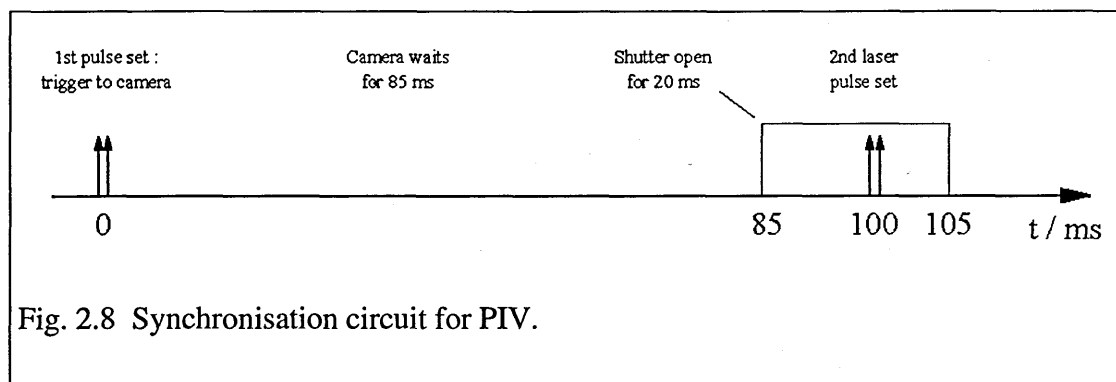
The velocity vector map contains a velocity vector for each interrogation region. The resolution of the vector map is therefore size of each region, which is typically of order 100 pixels, i.e. 1 % of the spatial resolution of the PIV image.

2.4.10 Synchronisation.

It is necessary to synchronise the exposure of the camera with the laser pulses in order to capture a successful PIV image. It is also desirable to keep the length of the exposure to a minimum, even if there is a bandpass filter in front of the camera, to minimise light from background sources such as flame luminosity.

The main factor in the synchronisation of PIV experiments using Nd:YAG lasers is the fixed flashlamp rep. rate which in this case was 10 Hz, i.e. the flashlamp cycles were separated by $100\ \text{ms} \pm 9\ \text{ns}$. The rate limiting step in taking a set of experimental images is the variable time required by the camera to take an exposure and save the image to disk. Since it took approximately 5 ms for the camera shutter to open, and the flashlamp cycle lasted only $300\ \mu\text{s}$, it would not have been possible to take an exposure simultaneously with the first pulse after the camera was ready.

The solution was to use the timing sequence shown in Fig. 2.8. The camera received a trigger pulse at the start of each laser flashlamp cycle. When the camera was ready to take the next exposure, the next trigger pulse started the trigger cycle, $t = 0$. The camera waited for 85 ms before opening the shutter for a 20 ms exposure, so that the shutter was open when the next set of laser pulses occurred, at $t = 100\ \text{ms}$. The image was then sent to the computer for storage.



If PIV images were to be taken from a non-stationary flow, for example the leading edge of an explosion, it would be necessary to synchronise the laser and camera with the arrival of the desired part of the flow at the measurement volume. In such circumstances, the system described in Section 6.2.4 would be used.

2.4.11 Data Rate and Storage.

The limiting step in taking DPIV images with a CCD camera was the time required to take and store the images. The number of images that can be taken in one set is determined by the number that can be stored on the PC hard disk.

For the experiments in Chapter 4, the size of each large area image was 2.77 Mb. The PC used most often had a hard disk of size 240 Mb, with 215 Mb free, equivalent to 77 DPIV images, or just over an hour of continuous data capture. It would not have always been possible to maintain the other experimental conditions for that length of time, for example the supply of seed particles might run out, or the air supply conditions alter. By 1995, PCs could have hard disks of size 2 Gb, equivalent to 722 images, though as CCD arrays become larger, the size of the image files will also increase.

Once a set of images had been taken and saved to the PC hard disk, they were immediately archived to a Trakker mini data cartridge tape system and also transferred to a network file server for analysis by DEC-Alpha workstations.

2.5 PIV analysis methods.

There are numerous analysis techniques for extracting velocity data from double-pulse PIV images. These include particle tracking, Young's fringe analysis, spatial autocorrelation, digital convolution by Fourier transform, optical correlation, cross-correlation, correlation-histogram map and 1-D analysis. These methods split into tracking methods and correlation methods; the seeding density will determine which method is used.

2.5.1 Tracking methods.

When the seeding density is low (PTV mode) the motion of individual seed particles is tracked between laser pulses to give the local velocity for that seed particle and therefore that region of the PTV image. There may be regions with no seed particles, so an interpolation routine can be used to "fill in" the gaps. Interpolation can also be useful to transform randomly distributed velocity vectors to a uniform grid for comparison with CFD models (Smallwood, 1992).

2.5.2 Correlation methods.

When the seeding density is high enough to perform PIV, it is not possible to track individual seed particles. Instead, the most common displacement of seed particles in an interrogation region is found using a correlation function. This gives the frequency of displacements between particle images in a region. The most common displacement is extracted from the correlation function and the velocity is calculated using Eq. (2.4). The confidence in the local velocity value lies in its statistical significance: it is more believable than particle tracking because many seed particles give the same velocity value. Correlation methods are reviewed thoroughly in Buchhave (1994) and Keane (1994). The most common are described below.

2.5.2.1 Autocorrelation.

If a single frame contains images of particles from two laser pulses with no distinction, an autocorrelation will be performed. This correlates all particle images with each other, resulting in an **autocorrelation function**. The correlation can be performed digitally, or optically with Fourier Transform lenses.

Digital autocorrelations can be performed using the Wiener Kintchine Theorem with Fourier Transforms :

- $F(R)$, the Fourier transform of interrogation region R , is calculated.
- $F(R)$ is multiplied by its complex conjugate, $F^*(R)$.
- The inverse transform of the product $F(R)F^*(R)$ gives the autocorrelation function $A(R)$.

or by a direct numerical correlation, calculating the expression

$$A(i, j) = \sum_{x,y} S(x, y) \cdot S(x + i, y + j) \quad (2.11)$$

for all (i,j) displacements, where $S(x,y)$ is the intensity at (x,y) in the image.

The autocorrelation function (Fig. 2.9) will contain a strong self-correlation peak at zero displacement, since every particle image correlates to itself. There will be a signal peak, the positive displacement peak, that corresponds to particle images from the first laser pulse correlating to images from the second pulse. There will be an equal peak at the corresponding negative displacement, corresponding to the reverse correlations. There will also be a number of noise peaks, corresponding to random correlations between images of different seed particles. In fact, the entire autocorrelation function will have 180° rotational symmetry about the origin. Directional ambiguity is unavoidable with autocorrelation methods and zero velocities cannot be measured due to the self-correlation peak.

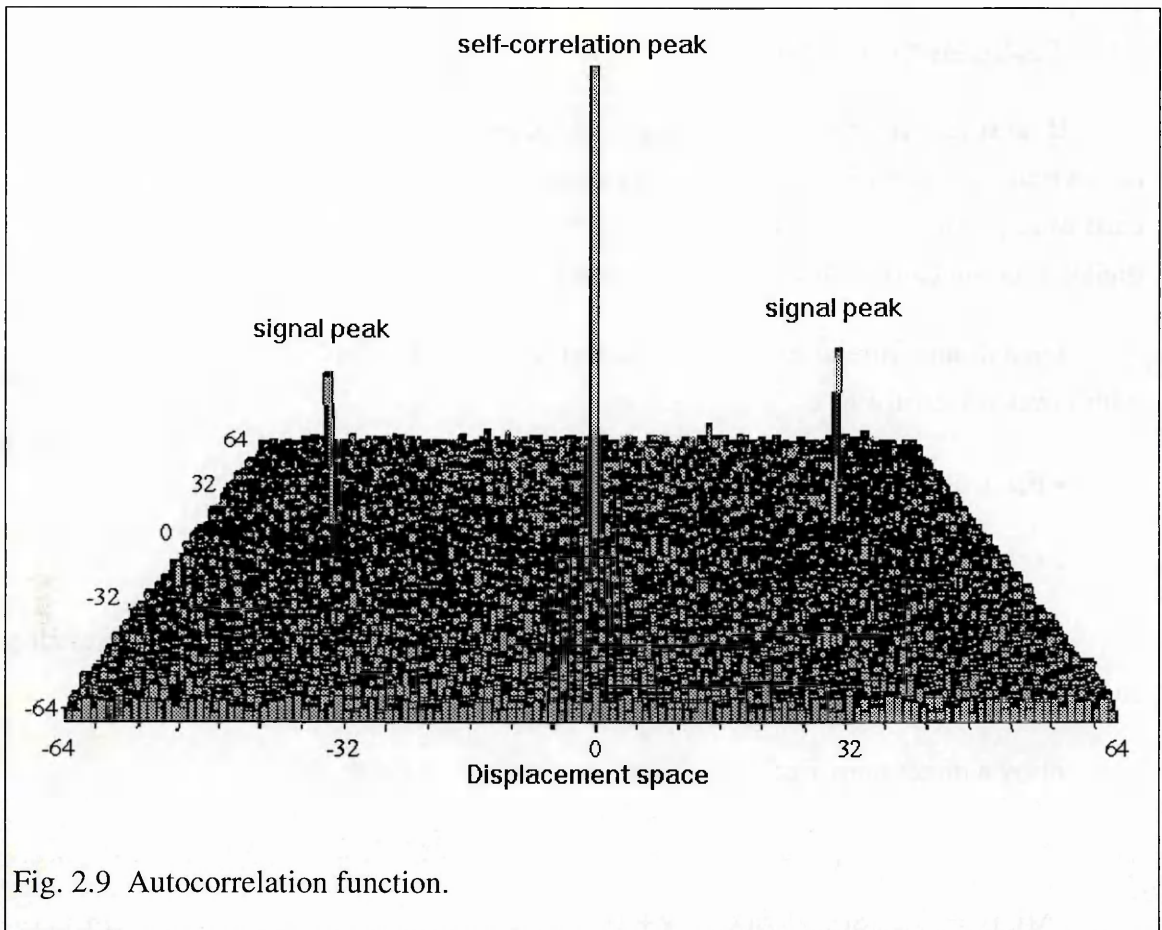


Fig. 2.9 Autocorrelation function.

2.5.2.2 Cross-correlation.

If the seed particle images from each laser pulse were captured on different frames, or are otherwise separable, a cross-correlation can be performed. This correlates each particle image from the first laser pulse in turn with each image from the second laser pulse. Cross-correlations are generally performed digitally, either with Fourier Transforms:

- $F_1(R)$ is the Fourier transform of region R, laser pulse 1.
- $F_2(R)$ is the Fourier transform of region R, laser pulse 1.
- The product $F_1(R) \cdot F_2^*(R)$ is calculated.
- The inverse transform of the product $F_1(R)F_2^*(R)$ gives the crosscorrelation function $C(R)$.

or by evaluating

$$C(i, j) = \sum_{x, y} S_1(x, y) \cdot S_2(x + i, y + j) \quad (2.12)$$

where S_1 is the signal at (x, y) in the first frame, S_2 is the signal in the second frame.

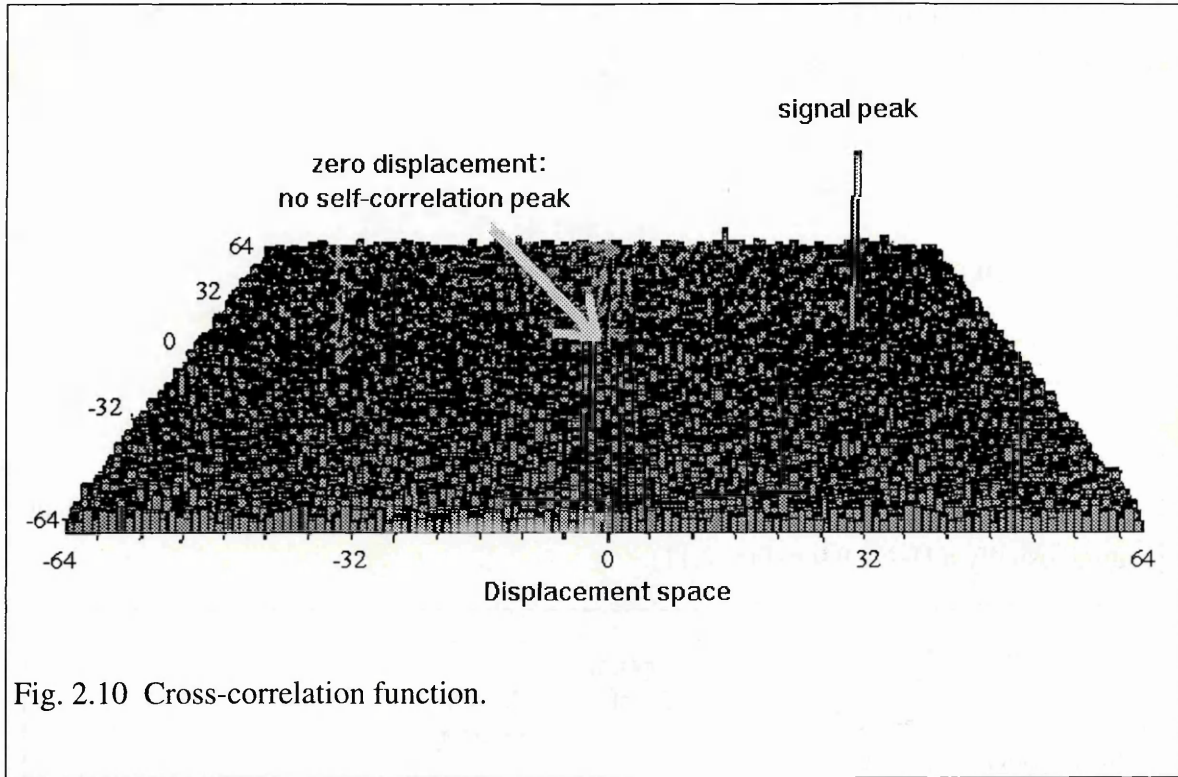


Fig. 2.10 Cross-correlation function.

The cross-correlation function (Fig. 2.10) will not contain a self-correlation peak and will have only one signal peak, corresponding to the displacement from the first to the second laser pulse. Thus, velocities down to zero can be resolved with the correct direction. The number of noise peaks will be lower, since the number of random correlations will have been effectively halved.

2.5.2.3 Optical vs digital methods.

Correlation functions can be performed either optically or digitally. Optical methods inherently perform the Fourier transforms instantaneously, though there will be

a bottleneck caused by limited data input and output speeds. There are questions about the durability and life of the non-linear optical components necessary.

Digital methods require extensive computational time to perform the Fourier transforms, though this will be reduced as more powerful processors become available. Digital methods require less hardware and setting-up time. Some digital analysis is necessary with all methods; to extract the signal peak and check for velocity continuity. When taking DPIV images, the whole process from data capture to vector map production will be digital.

2.5.3 Optical analysis methods.

2.5.3.1 Young's fringe method.

An interrogation region of the PIV image is illuminated with a coherent light source, usually a HeNe laser (Fig. 2.11).

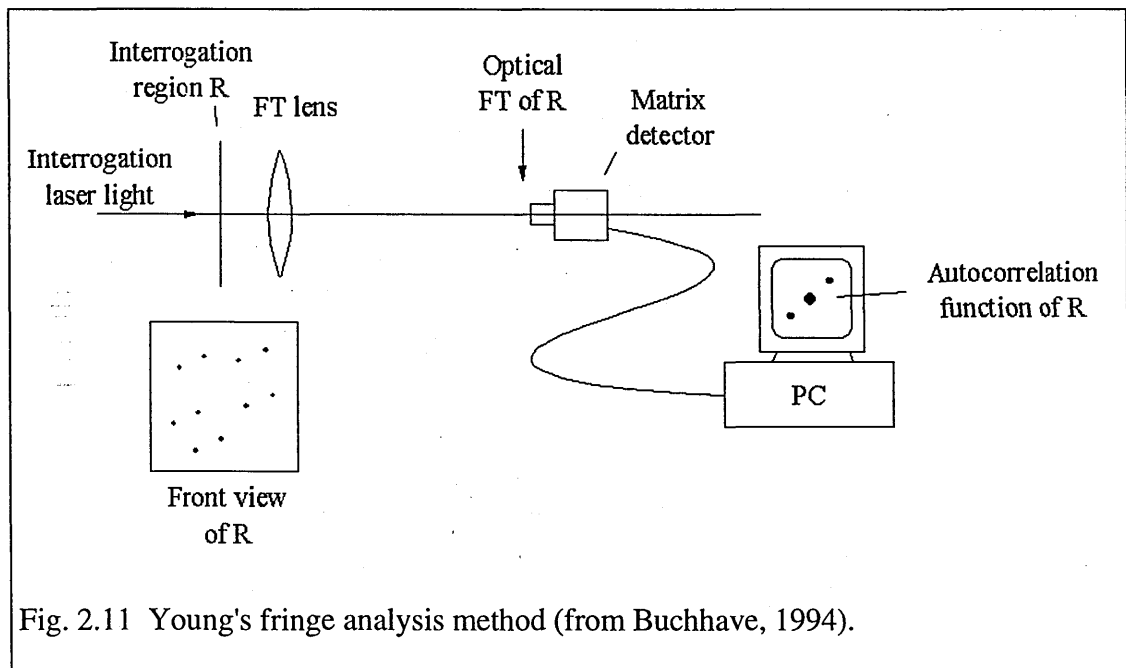


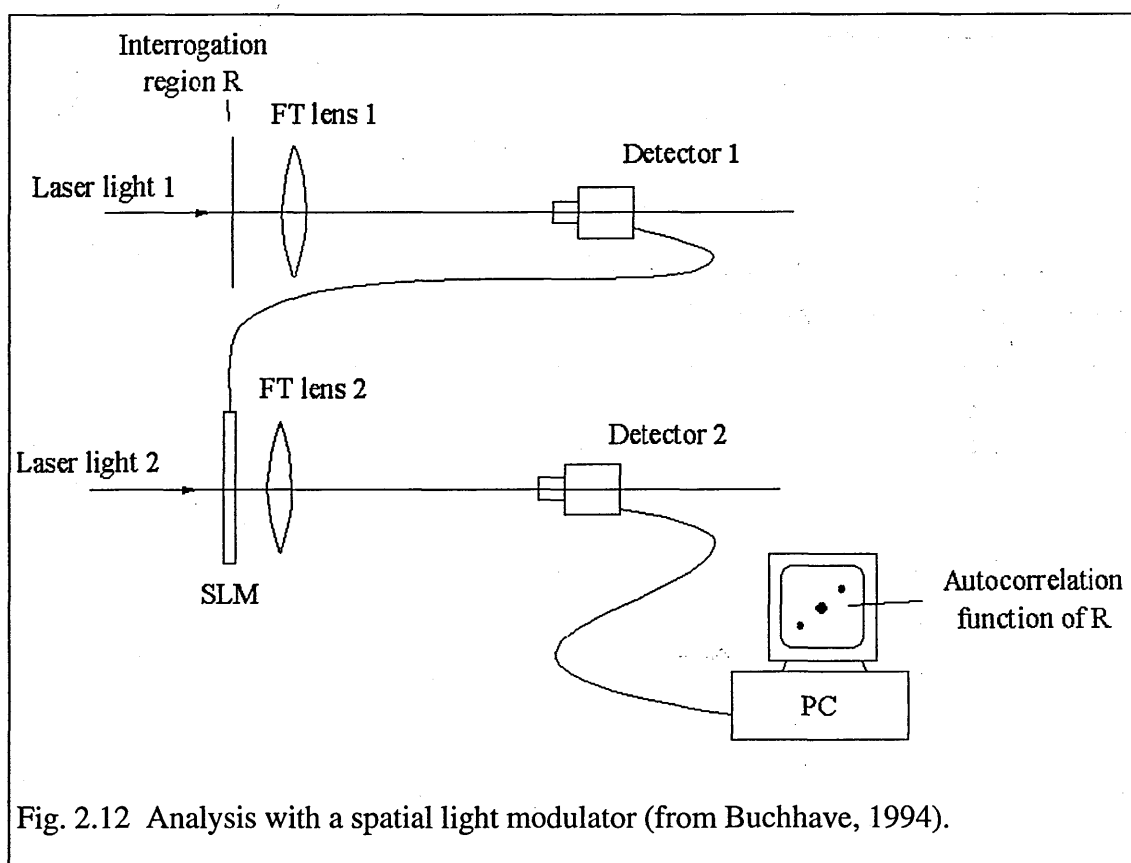
Fig. 2.11 Young's fringe analysis method (from Buchhave, 1994).

A lens is used to Fourier transform the region. The transform is squared to form the power spectrum, detected and stored on a computer. After digitisation, the power spectrum is Fourier transformed numerically, to yield the autocorrelation function. The

location of the signal peak is detected and converted to velocity information. The procedure for extracting the velocity vector is repeated for all interrogation regions in the PIV image, to produce the velocity vector map. This method was the most commonly used when early conventional photographic PIV was being performed (e.g. Dudderar and Simpkins, 1977).

2.5.3.2 Spatial light modulator method.

An all optical processing method can be implemented using a spatial light modulator (SLM), illustrated in Fig. 2.12.



This is a programmable component, e.g. liquid crystal display, whose optical transmission in an array of cells may be controlled electronically. These components may work by phase or amplitude modulation. The first Fourier transform of the interrogation region is recorded by video camera 1 and relayed to the SLM. The following Fourier transform results in the autocovariance of the region, convolved with the Fourier

transform of the plane wave, i.e. located at the focal point for the plane wave. Video camera 2 records this function, from which the velocity vector can be extracted.

2.5.3.3 Photoreactive crystal method.

A photoreactive crystal is a non-linear optical crystal in which an optical field can be stored as a volume hologram (Buchhave, 1994).

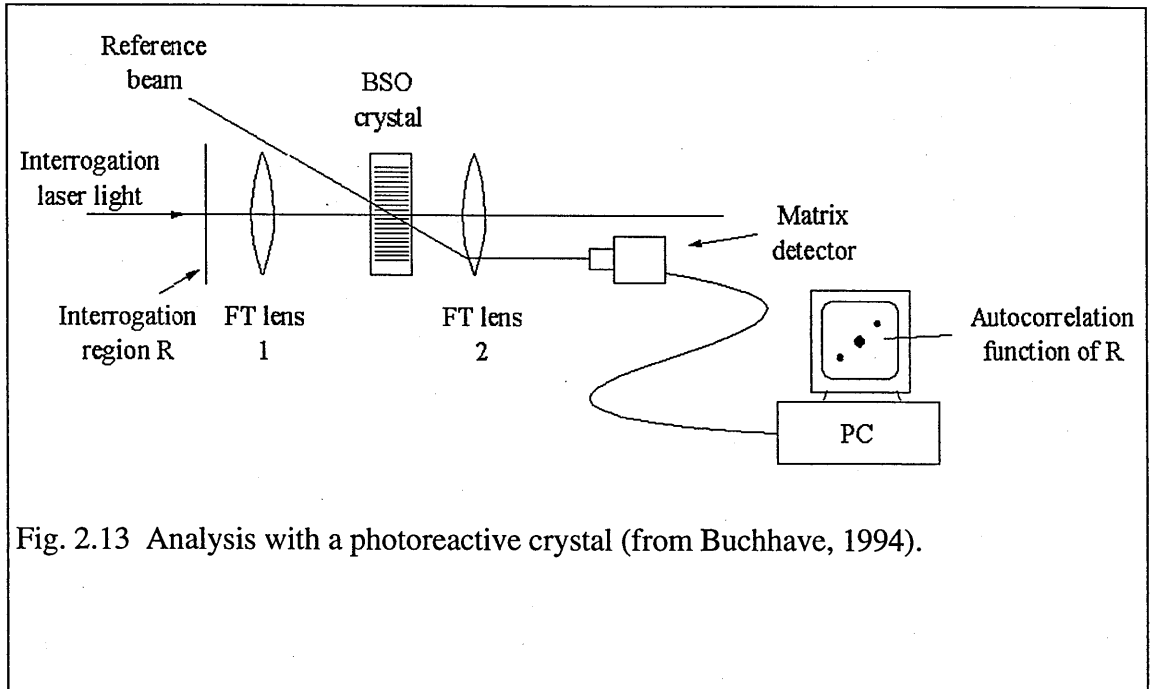


Fig. 2.13 Analysis with a photoreactive crystal (from Buchhave, 1994).

In Fig. 2.13, the BSO crystal stores a hologram of the Fourier transform of the interrogation region, a, by means of a reference beam. This beam is turned off, after which the Fourier transform of the object field is multiplied by itself through the phase modulation in the crystal. The result is an autocovariance function of the interrogation region. The writing time constants are of the order of seconds with HeNe lasers, or 10^{-6} s with pulsed lasers. The hologram will be stable in darkness, but can be erased with uniform illumination.

2.5.4 Digital analysis methods.

2.5.4.1 Digital-photographic PIV.

A technique combining the very large resolution of photographic PIV images with the advantages of digital analysis consists of digitising each interrogation region. This is usually achieved with a CCD camera, typically with array of size 512 x 512 pixels. A translation stage moves the camera accurately between regions.

The digital analysis of an interrogation region is performed on a computer, often with commercial software and dedicated hardware such as array processors. The analysis algorithms are generally based on Fourier methods.

2.5.4.2 Digital PIV.

DPIV images are captured and stored in a digital format, allowing the analysis to be performed wholly on a computer. It is a straightforward matter for the analysis software to split the electronic image into interrogation regions and perform the appropriate correlation function, followed by peak extraction.

2.5.5 Features of analysis.

Supplementary to the basic correlation of each interrogation region in an image, PIV analysis software will generally include some of the following features, in order to generate the best possible velocity vector map :

- Variable interrogation region size.
- Variable overlap of regions.
- Centroiding for greater accuracy.
- Continuity check between neighbouring vectors.
- User input when direction is uncertain.
- User input when no clear velocity is found.

These features are explored in more depth in Chapter 4.

2.5.6 Error analysis in PIV

The errors present in PIV velocity vector maps occur in two types:

- the error, or uncertainty, in the value of a velocity from a correct correlation,
- the error of extracting a wrong velocity from a correlation function.

2.5.6.1 Error in value of velocity.

When a displacement vector is extracted from a correlation function, it is converted to a velocity using Eq. (2.4). Assuming the vector is derived from true particle sets, the error in the velocity value will be due to :

- errors in the value of the pulse separation Δt ,
- errors in the displacement Δx .

Using a fast photodiode and digital oscilloscope, typical pulse separations in the range 20-600 μs can be measured with an accuracy of $\pm 0.1 \mu\text{s}$, an upper limit of 0.5 %.

The displacement value is comprised of the number of pixels and the magnification factor. The magnification factor can be accurately determined, to less than 1 % error, with a calibration image of a ruler.

For the experiments carried out here, the typical displacements on the chip were approximately 10-20 pixels. Discretisation involves an error of ± 1 pixel, which therefore corresponded to 5-10 % of the displacement, clearly dominating the other sources of error.

The error due to discretisation can be reduced in two ways. First, larger displacements can be used, e.g. a ± 1 pixel error in a displacement of 100 pixels corresponds to only 1 % of the measured velocity. The limit on lengthening the displacement, for a given measurement region, is that it would use more of the fixed chip area on the CCD camera. This would make it less likely that complete particle image sets would fall within an interrogation region, reducing the number of correlations drastically. If the pulse separation were lengthened, within the constraints of the apparatus, particle image sets would lose coherence, i.e. they would be further apart, compared with the

average spacing between seed particle images. It would be more difficult to perform a correlation under such circumstances.

The second way to reduce the discretisation error is to resolve particle image positions to sub-pixel accuracy (Keane and Adrian, 1990; Guezennec and Kiritsis, 1990; Willert and Gharib, 1991), which is achieved by

- recognising pixels which correspond to one particle image,
- calculating the centre of mass, for example based on each pixel's intensity.

This method assumes that it is legitimate to calculate the centre of mass based on the centre of Mie scatter intensity. Different centroiding strategies are described in Section 4.4.8.

2.5.6.2 Extracting the wrong vector.

When generating PIV images from any but the most simple flows, some velocity vectors extracted from the correlation function will simply be the wrong vector, i.e. they come from multiple random correlations between images of different seed particles. This case occurs most in monochromatic two-pulse PIV.

The reason may be either that there is not sufficient seeding density to produce a significant signal correlation, or that there is too much seeding density, causing noise correlations to be as significant as signal ones. These extremes illustrate the difficulty in producing the correct seeding density in the flow being studied.

The common method for determining if a vector is correct is to compare it with neighbouring vectors, within certain criteria, on the assumption of continuity of flow. If a vector does not meet the criteria, in terms of its magnitude or direction, it can be replaced with a better vector. Ultimately, the error due to bad vectors can be expressed as the percentage of interrogation regions for which "good" vectors cannot be produced and are thus left blank. Blank vectors can be "filled in" by interpolating from the neighbouring vectors (see 4.4.10).

2.6 Summary.

PIV has become well established as a laboratory technique for making instantaneous, two dimensional velocity measurements, and is rapidly being developed into reliable commercial systems. It is potentially useful as a tool for investigating turbulent flow fields, for example in the vicinity of a flame-front. Completely digital systems are expected to eventually become the preferred method. Many applications require the flow direction to be resolved unambiguously, and a mature technique must include this feature.

Future development of PIV is likely to concentrate on three areas :

1. increasing the speed of vector map generation, currently dominated by computing time.
2. reducing the cost of commercial systems to customers.
3. extending the technique range to wider velocity ranges, harsher environments and three dimensions.

The next chapter describes an investigation into the implementation of a completely digital PIV system, with the aim of making full-field velocity measurements in the vicinity of a flame-front.

Chapter 3.

Investigation of DPIV: simulation and experiment.

3.1 Introduction.

This Chapter describes an investigation of the issues involved in implementing a PIV system, starting with the standard two-pulse, monochromatic technique. A program was written to generate simulated images in order to provide initial evaluation of the analysis method. This allowed the analysis software to be written and tested. It also allowed likely optimum values for experimental parameters to be investigated. The analysis initially used Fourier transform methods, but switched to a direct numerical calculations. Some experimental two-pulse DPIV images were taken from a uniform flow to demonstrate the system. When applied to non-uniform flows, the drawbacks of the standard system were illustrated.

3.1.1 Digital PIV.

The issues involved in a choice between photographic and digital PIV were discussed in Section 2.3.10. Digital PIV is likely to increasingly become the preferred option as video and CCD technology advances. The investigations of PIV reported here concentrated completely on the digital method, although a comparison experiment with photographic PIV would have complemented the work.

3.2 DPIV Simulation.

A computer program was written to generate simulated two-pulse DPIV images using a Monte-Carlo method in order to :

- allow the analysis software to be written and tested,
- allow the determination of the important parameters in obtaining good data and the optimum values of these parameters.

These images simulated laminar or near-laminar flows.

3.2.1 Image generation program.

A program was written to generate an array file, equivalent to a CCD image of typical size 600 x 400 pixels. The program was written in C, using a network of Digital workstations, running the UNIX environment. For each generated particle, a pair of single pixel positions were determined, equivalent to the images that would be produced by one seeding particle in a two pulse DPIV image.

An example of part of a generated image is shown in Fig 3.1. The small white squares are pixels where a particle image has been generated. These images occur in pairs separated by a user-specified displacement, such as particle images A and B, separated by displacement $\underline{d}$.

The position of the first particle image of each pair was generated with a standard random number generator, included with the network UNIX system. The position of the second particle image was then calculated by applying the common displacement to

the first particle image position. A value was assigned to the array positions of each generated particle, which was a random integer in the range 1 - 100. This simulated the

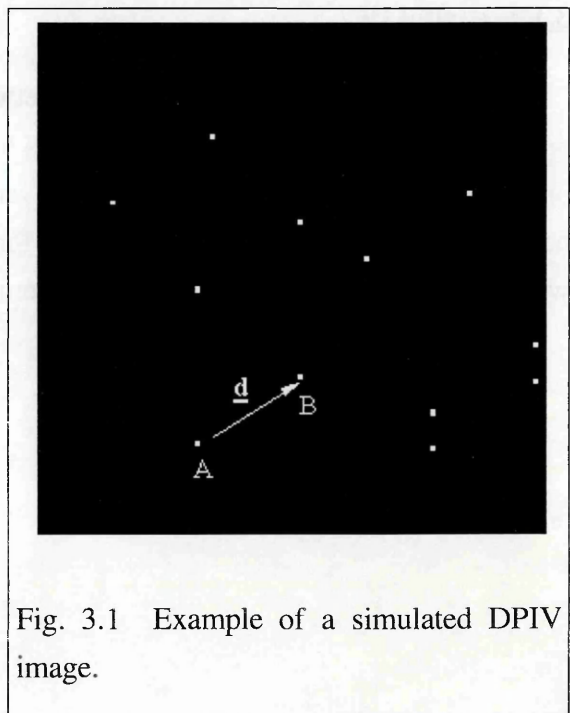


Fig. 3.1 Example of a simulated DPIV image.

variation of the signal intensity from seed particles, depending on their position in the laser sheet. All other array elements contained the value zero. The simulated DPIV images were written to a file, to be processed by the PIV analysis software.

In reality, seed particle images often extend over more than one pixel (see 2.4.9.1). However, prior to recording experimental images, which would show how particle images were imaged onto a CCD array in reality, the generation of single pixel images was the most appropriate strategy.

The variable parameters in the program were :

- the common displacement between the two images of a particle, equivalent to the velocity of the simulated flow,
- the number of particles to be generated in the array (seeding density).

3.2.1.1 Displacement.

For these simulations, the displacement was often taken as 20 pixels. The systematic error in the analysis of ± 1 pixel then represented a 5 % error on displacements and therefore velocities. The use of a shorter displacement would give a larger systematic error, unless sub-pixel accuracy were used. A longer displacement would reduce the spatial resolution of the velocity map, given the fixed size of the CCD array, since larger interrogation regions would be required.

3.2.1.2 Seeding density.

The seeding density was specified in terms of the percentage of array pixels that contained a seed particle image, i.e. twice the density of seed particles. If an interrogation region contained more particle pairs, the correlation function would have a larger correlation peak, resulting in greater confidence in a vector. However, as the number of particles increases, there will also be an increase in the number of noise correlations, i.e. correlations between images of different particles. If the result were a lower signal to noise ratio, it would be less likely that the correct displacement could be extracted from the correlation function.

3.2.2 Analysis software.

Software was written to read simulated images and perform an analysis to extract a velocity vector map. This software was to be used when experimental DPIV images were obtained, so the simulated images were useful for debugging and testing the algorithm. Initially, the program utilised FFT routines in the CLIPS suite, developed at Cranfield University by N. P. Tait (see 4.4.1). The later program, using direct numerical calculations was "standalone".

The basic algorithm for analysing PIV images is as follows. An image is read into memory and correlation is performed on each interrogation region in turn. The best signal peak is extracted from the correlation function and held in memory. The array of signal displacements from each region is written to the output file, which can be displayed as the velocity vector map.

3.2.3 FFT analysis.

The initial analysis used the double Fourier Transform method (see 2.5.2.1), implemented with a Fast Fourier Transform algorithm. An example autocorrelation function is shown in Fig. 3.2, for an interrogation region of size 128 x 128 pixels.

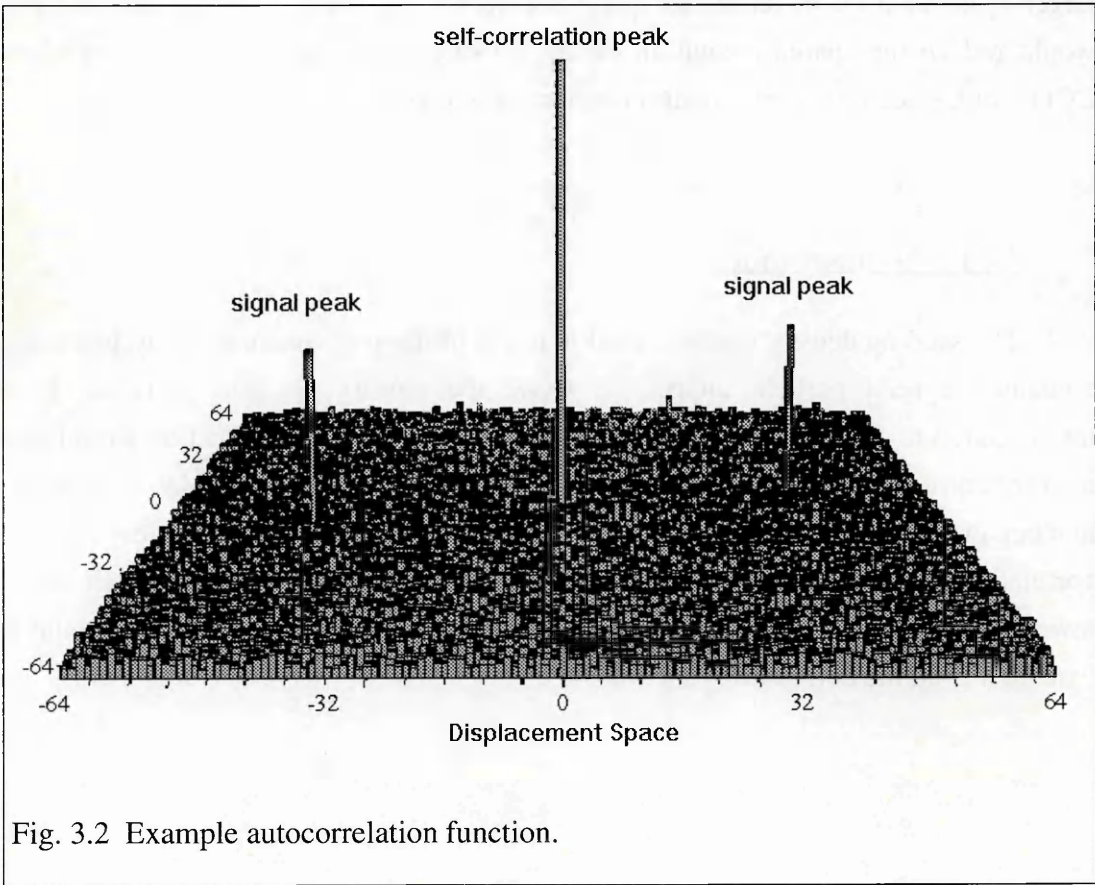


Fig. 3.2 Example autocorrelation function.

The base is displacement space, with zero displacement at the centre. The height of a peak indicates the number of correlations for that displacement in the autocorrelation function. The principle features described in Section 2.5.2.1 are clearly visible; the central self-correlation peak and two symmetric signal peaks, with low background noise. In fact, the signal peaks have the same height, which is exactly half the height of the self-correlation peak.

3.2.3.1 Interrogation region size.

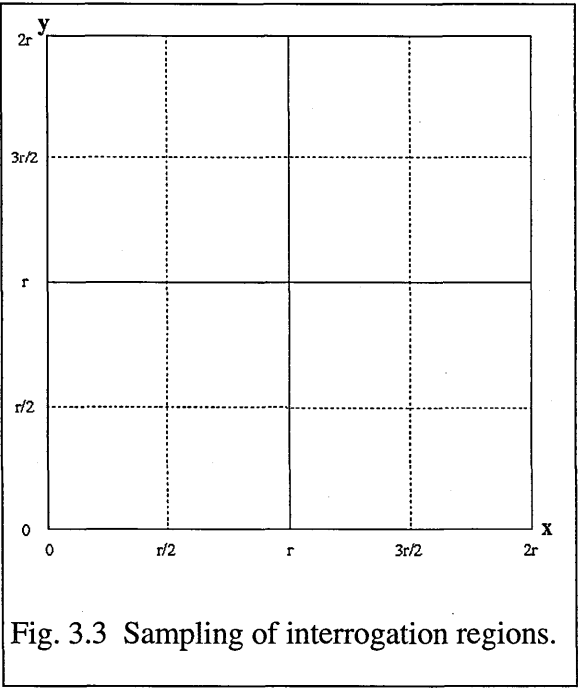
With Fourier Transform methods, the size of each interrogation region must be a power of two. This is not normally a constraint with photographic PIV, since the film has such a large spatial resolution. Usually, a 512 x 512 pixel CCD will be used to image one interrogation region at a time, with whatever magnification is desired.

With DPIV the resolution of the image is fixed at the time of acquisition, so the size of interrogation region used in the analysis becomes important. The minimum size of the region must be typically two to three times the displacement vector, in order to have sufficient complete particle pairs within a region (Willert and Gharib, 1991). Without sub-pixel accuracy a typical minimum displacement is 20 pixels, such that the discretisation error is only 5 %. This implies an interrogation size larger than 40 pixels. Thus, if the CCD camera has an array of 600 x 400 pixels, the interrogation region size can only be 256, 128 or 64 pixels.

3.2.3.2 Sampling Rate.

The Nyquist criterion states that the maximum frequency signal that can be resolved is half of the sampling frequency (Connor, 1982; Willert and Gharib, 1991). It is common to adopt this criterion by sampling interrogation regions with an overlap of half a region size, where the vector map resolution is the size of the interrogation regions.

Fig. 3.3 illustrates an image of size $2r$, where r is the chosen size of an interrogation region. The coordinates of the nine interrogation regions that would be used with $r/2$ overlap are shown in Table 3.1.



<u>Region</u>	<u>x-start</u>	<u>x-end</u>	<u>y-start</u>	<u>y-end</u>
1	0	r	0	r
2	$r/2$	$3r/2$	0	r
3	r	$2r$	0	r
4	0	r	$r/2$	$3r/2$
5	$r/2$	$3r/2$	$r/2$	$3r/2$
6	r	$2r$	$r/2$	$3r/2$
7	0	r	r	$2r$
8	$r/2$	$3r/2$	r	$2r$
9	r	$2r$	r	$2r$

Table 3.1 Interrogation region co-ordinates.

Often the velocity maps that are displayed show vectors for all interrogation regions, implying a better resolution than exists. This becomes clear when a spurious feature in an image causes a bad vector in four neighbouring regions.

The spatial frequency of the flow velocity "signal" is really the relevant scale of turbulence, i.e. the scale over which the velocity varies, given the resolution of the image. If the resolution of the PIV image is chosen so that the interrogation region size is close to this scale, neighbouring velocity vectors will vary significantly, causing the velocity vector map to be difficult to analyse. There will also be significant variations of velocity within an interrogation region. With PTV, this is not always a major problem, since sets of particle images are distinct and more easily resolved. In the high seeding density PIV regime, accelerations in an interrogation region reduce the correlation signal, making the extraction of a local mean velocity less likely.

An alternative strategy is to adjust the parameters of the DPIV images so that the typical interrogation region size is somewhat smaller than the appropriate turbulence scale. The velocity will then vary far less between neighbouring regions, so the Nyquist criterion can be satisfied by stepping a whole interrogation region side. The co-ordinates of the four equivalent interrogation regions, sampling every r pixels are shown in Table 3.2.

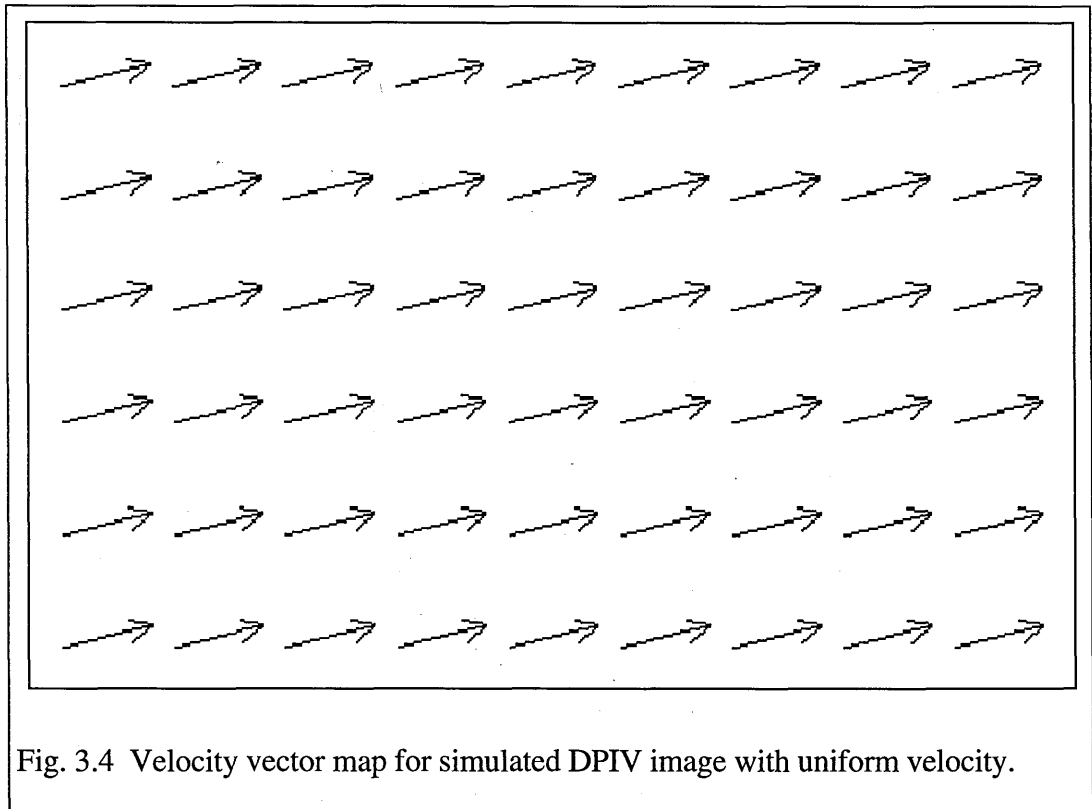
<u>Region</u>	<u>x-start</u>	<u>x-end</u>	<u>y-start</u>	<u>y-end</u>
1	0	r	0	r
2	r	$2r$	0	r
3	0	r	r	$2r$
4	r	r	r	$2r$

Table 3.2 Co-ordinates of interrogation regions with no overlap.

Using this method of sampling the DPIV image, the resolution of the vector map is clear and spurious features in the image affect only one velocity vector. Lone "bad vectors" are much easier to recognise and correct by a post-correlation routine (see 4.4.9). As larger CCD arrays become available, the constraints of this approach will become less important.

3.2.3.3 Uniform velocity images.

Simulated DPIV images with a uniform velocity throughout each image were successfully analysed with the software, producing velocity vector maps like the one shown in Fig. 3.4, which used an interrogation region size of 64 pixels. There is one arrow for each interrogation region, corresponding to the signal displacement vector. For a real image, this would be scaled by the pulse separation to give the actual velocity. In this example, all the vectors are the same, as expected for the idealised data.



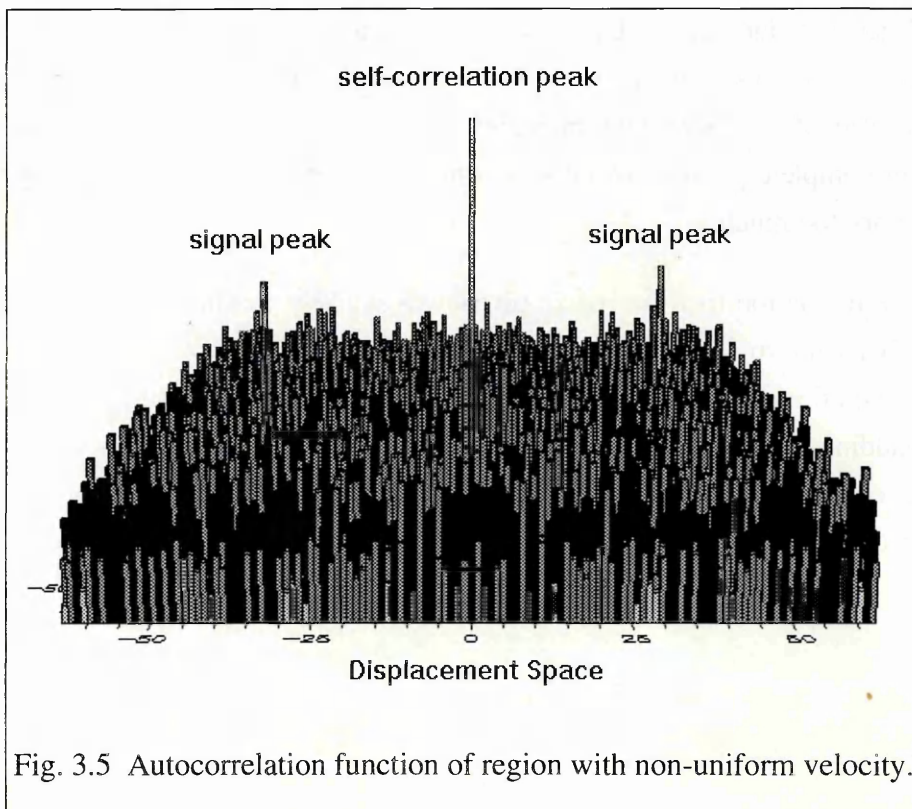
The autocorrelation functions for these images are nearly ideal, like Fig. 3.2. They possess 180° rotational symmetry about the origin and which of the two signal peaks is extracted depends on the order of the search routine. If the predominate flow direction is known, therefore, it is possible to include this in the peak extraction routine, by inspecting only the appropriate half of the autocorrelation function and defining the order of the search. This method reduced the processing time by a small amount. A more significant reduction would be gained if the autocorrelation routine could include only correlations in the preferred direction.

3.2.3.4 Non-uniform velocity images.

Within a realistic DPIV image, there will be small variations of displacements between particle image pairs. One of the important aspects of good PIV analysis is to have an algorithm that manages to incorporate such variations, to give good results.

To produce more realistic simulations, a feature was added to the simulation program that applied a random variation on the displacement between a particle image pair, up to a user-specified maximum percentage, typically 3-5%. A large variation would undermine the assumption that the local velocity within an interrogation region is constant.

The autocorrelation functions of such images deviated from the ideal, since the signals in the autocorrelation function did not all overlap. This caused the signal peak to spread, with its height reduced toward that of the noise correlations, such as the example shown in Fig. 3.5. It became less likely that the signal peak would be higher than noise peaks by the chosen signal to noise ratio, or even that it would be the highest peak. Consequently, regions began to produce either wrong velocity vectors, or none at all. The vector map in Fig. 3.6 shows the vector map from a simulated image with 5% maximum velocity variation, which caused 16% of the vectors to be wrong.



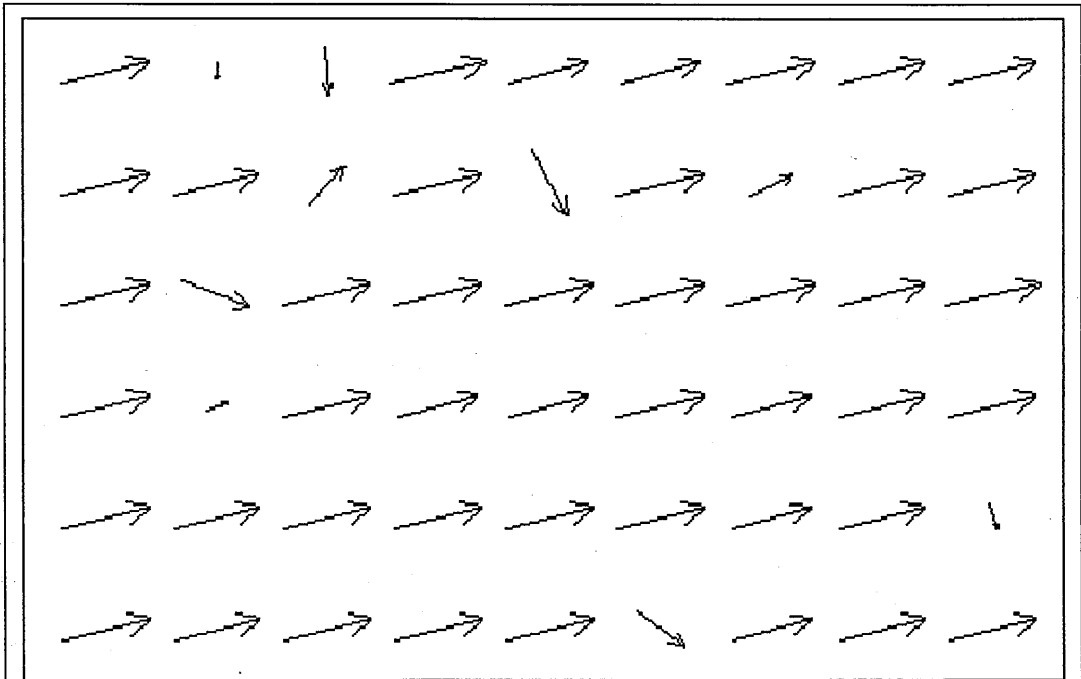


Fig. 3.6 Velocity vector map from simulated DPIV image with 5 % maximum velocity variation.

3.2.4 Non-FFT analysis.

When the data in the DPIV images deviated from the ideal, it became more important to optimise the important analysis parameters. One of the principle factors was the size of the interrogation region. It needed to be large enough to contain sufficient complete particle image sets, while small enough that the velocity within it did not vary too much.

The restriction to a size of 2^n pixels was unlikely to allow the optimum size of region. If an interrogation region size not equal to a power of 2 was required, FFT analysis would require that each region were enlarged to the next highest power of 2, using padding with zeros. Such an algorithm was tested on some simulated images, and the correct vectors could be extracted. However, the discontinuity created by padding the region with zeros appeared to create noise in the autocorrelation function.

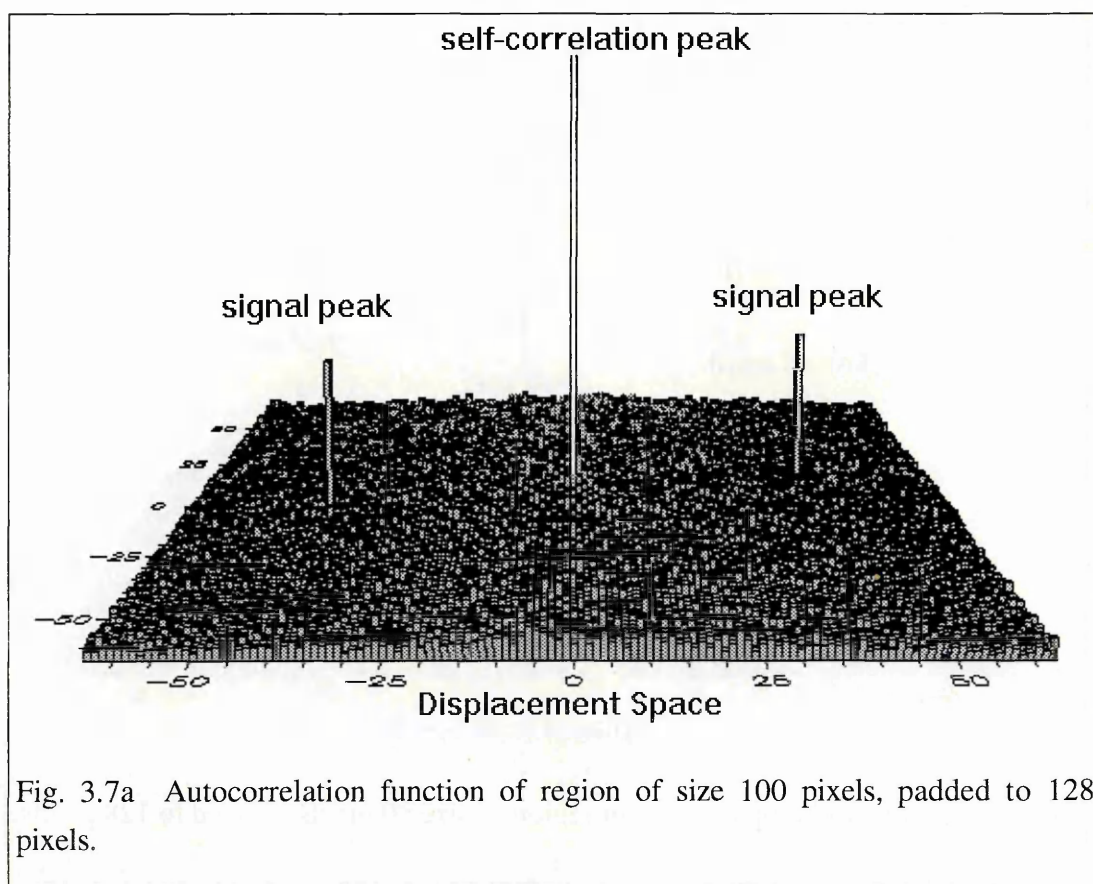


Fig. 3.7a Autocorrelation function of region of size 100 pixels, padded to 128 pixels.

In Fig. 3.7a, an interrogation region size of 100 pixels has been padded to 128 pixels. This is still close to an ideal autocorrelation function. In Fig. 3.7b, a region of size 80 pixels has been padded to 128 pixels. Increased background peaks around the self-correlation peak can be seen, some of which are of comparable height to the signal peaks. With real PIV images, where acceptable signal to noise ratios would be even more difficult to achieve, it was expected that the noise caused by this padding would hinder the successful extraction of the velocity vector map. It would be difficult to design an analysis algorithm that could predict when padding would cause significant noise in the autocorrelation function. Consequently, the analysis algorithm was changed to perform a direct numerical correlation.

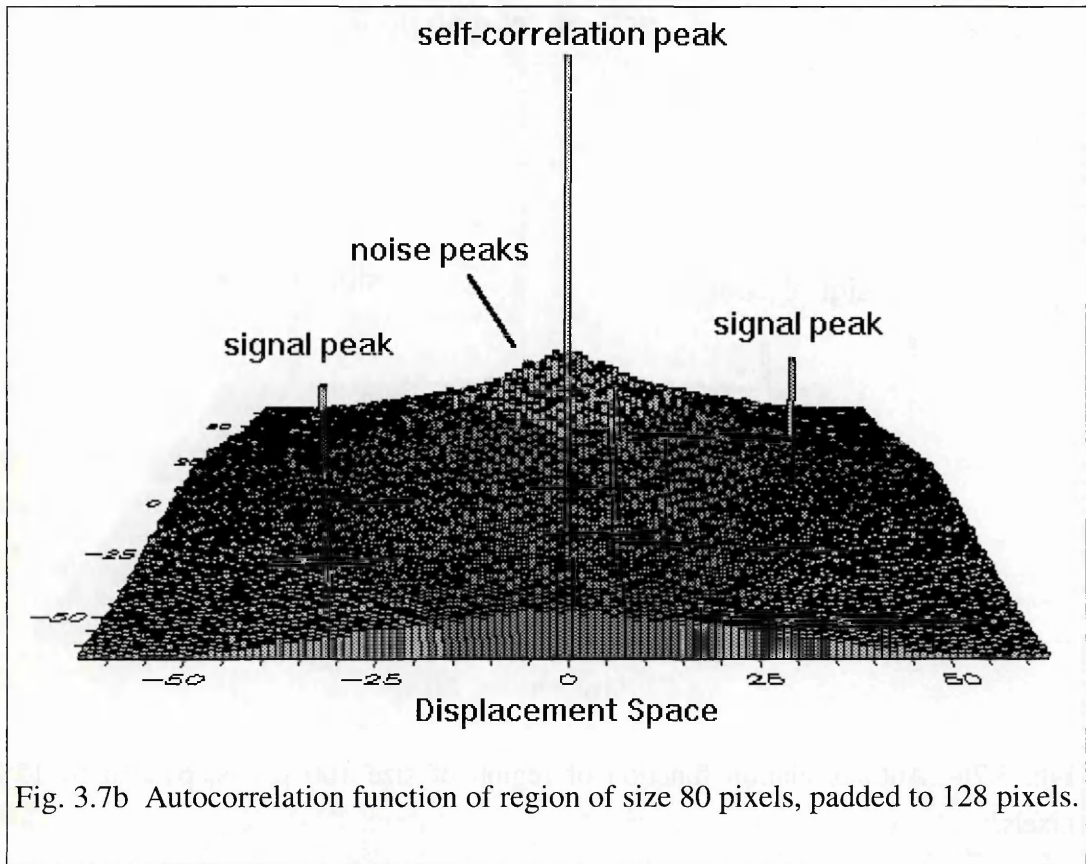


Fig. 3.7b Autocorrelation function of region of size 80 pixels, padded to 128 pixels.

The standard autocorrelation function is mathematically and computationally very simple :

$$A(i,j) = \sum_{x,y} S(x,y) \cdot S(x+i,y+j) \quad (3.1)$$

where $A(i,j)$ is the signal in the autocorrelation function at displacement (i,j) , $S(x,y)$ is the signal at (x,y) in the interrogation region of the PIV image. The autocorrelation function calculated in this way gave exactly the same result as the Fourier Transform method, though with a time penalty.

3.2.4.1 Computation time optimisation.

In abandoning FFT analysis methods, the time required to analyse each interrogation region, and hence a whole PIV image was increased. The time used by the processor for performing correlation functions was more than 99% of the total

analysis time. In order to reduce the correlation time to a minimum, standard programming optimisation methods were employed :

- The image was stored as a one dimensional array in memory.
- Where possible, nested loops were changed to single loops.
- Where appropriate, binarisation improved speed.
- The calculations were performed on particle image positions, not pixels.

3.2.4.2 Binarisation.

Binarisation converted each pixel in an image to one of two values: unity if it contained a seeding particle image, or zero if it did not. A threshold signal level, T , was used to discriminate. There were then only four possibilities for each calculation in the autocorrelation:

$$1) A(i,j) = 1 \times 1 = 1.$$

$$2) A(i,j) = 1 \times 0 = 0.$$

$$3) A(i,j) = 0 \times 1 = 0.$$

$$4) A(i,j) = 0 \times 0 = 0.$$

In the program, the *multiplication* could be replaced with a *comparison* which was much quicker to compute :

$$\text{IF } S(x,y) > T \text{ AND } S(x+i,y+j) > T \text{ THEN } A(i,j) = A(i,j) + 1$$

The applicability of binarisation is explored further in Section 4.4.4.

3.2.4.3 Pixels vs positions.

The most significant time saving was achieved by identifying actual seeding particle images, using the background threshold, and creating an array of image

positions. Since up to 90% of the interrogation region contained no particle image, most of the calculations in the correlation function were actually multiplying background intensities, effectively performing calculation 4) $A(i,j) = 0 \times 0$.

The correlation function was altered to calculate the displacement between all combinations of particle image *positions* in the list, rather than performing a multiplication between all pairs of *pixels* in the interrogation region. This is described in detail in Section 4.4.5.

The implementation of these methods reduced the analysis time for a DPIV image from two hours to ninety seconds on a DEC-Alpha 3600 workstation. This compared with approximately twenty seconds for an FFT analysis on a workstation.

3.2.4.4. Border regions.

When attempting to increase the signal to noise ratio in the autocorrelation function, it can be difficult to reduce the number of noise correlations, which occur between all pairs of images that are not from the same particle. Many of these noise correlations are actually caused by unpaired particle images; those that do not have a particle image pair in the region. These particles contribute only noise to the correlation function. They can be unpaired for two reasons:

- the particle moved into or out of the laser sheet between pulses, hence there is no image pair in the DPIV image. The only solution is to widen the laser sheet.
- the image pair fell outside the arbitrary border of the interrogation region (Fig. 3.3). If such image pairs could be included in the autocorrelation function, they would increase the signal peak.

The analysis algorithm was altered to include a border region, such that if an image pair fell just outside the interrogation region, it could still contribute to the autocorrelation function for that region.

This is illustrated in Fig. 3.8. The inner square is the interrogation region, of length r . It is surrounded by a border (shaded), of width b . The region and border combine to form the sample, of length $s = r + 2b$. Consider the particle images shown, where the true displacement is from A to B, the same as from C to D. Particle C's image pair is D, lying outside the region, but inside the border. All correlations *from* images in the border *to* images in the region were counted. However, only correlations *from* images in the region *to* images also in the region were counted.

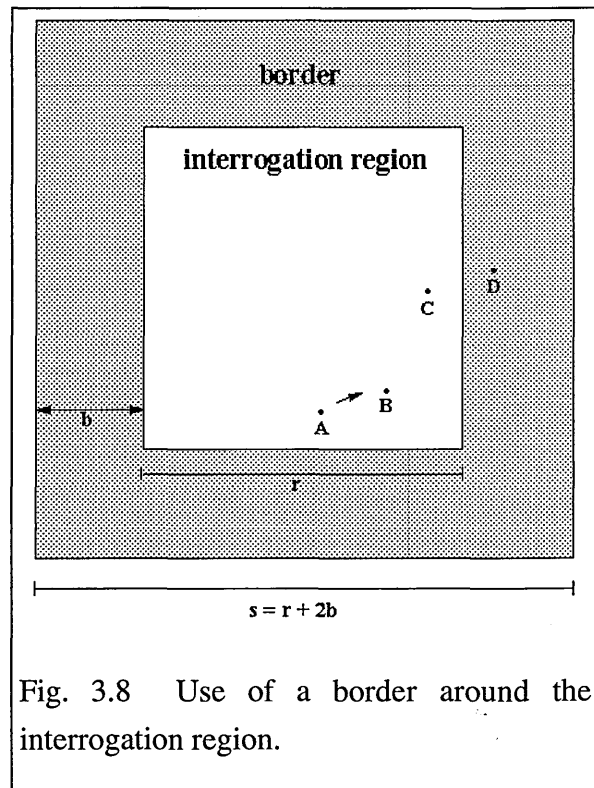


Fig. 3.8 Use of a border around the interrogation region.

Each image in the border correlates to interrogation region images in one direction only, causing the correlation function to become asymmetric, i.e. there will be a count for displacement $D \rightarrow C$, but not one for displacement $C \rightarrow D$. Though a signal correlation may be gained, many noise correlations will also be added since D correlates to all other particle images in the interrogation region. (In this example, the gained correlation $D \rightarrow C$ is in the wrong direction). This method may be of use if one could

- guarantee that every border-image contributed a signal correlation.
- prevent noise correlations, i.e. identify the border-image's image pair.

It is possible that with very low seeding densities, e.g. PTV, a border may help the analysis. However, in attempting to construct an automatic analysis algorithm for the high density regime, the potential gain of border regions did not seem to be sufficiently significant, so the idea was abandoned.

3.2.5 Optimum parameters.

Simulations were performed with a variety of seeding densities, velocity variation and interrogation region sizes. The percentage of extracted vectors that matched the input values was recorded for each set of analysis values.

Fig. 3.9a shows the variation of success rate against interrogation region size, normalised by the common displacement, for a uniform velocity distribution. The minimum interrogation region size for good analysis appeared to be approximately three times the displacement, which agrees with the findings of Willert and Gharib (1991). This simulation did not predict the maximum size because it was not possible to alter the velocity throughout the image.

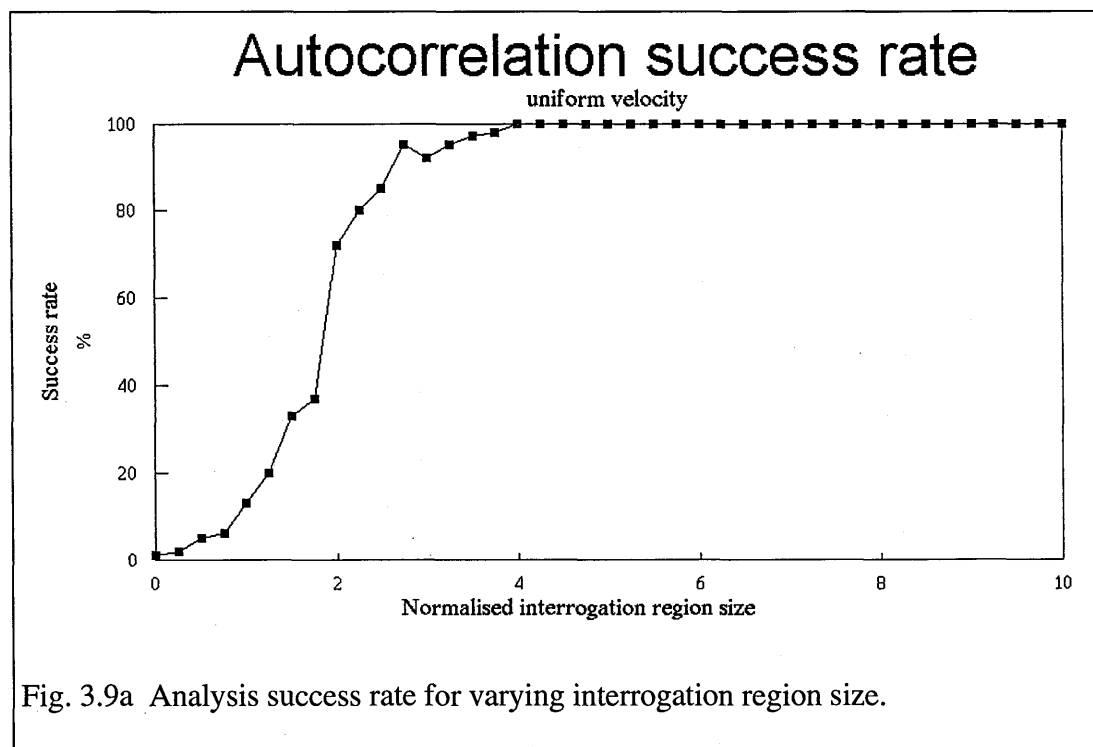
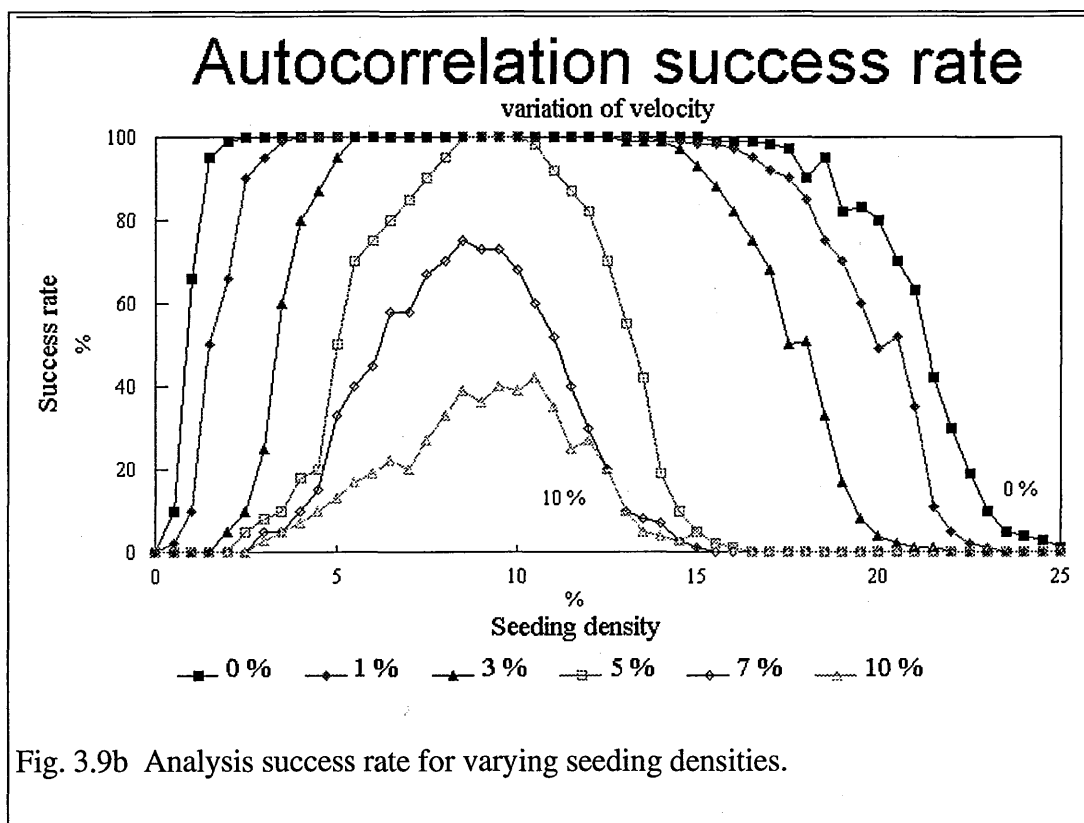


Fig. 3.9a Analysis success rate for varying interrogation region size.

Fig. 3.9b shows the variation of success rate for different seeding densities and for different maximum percentage velocity variations. When the velocity varied by more than about 5%, the success rate became poor, considering the simulated data consisted of idealised single pixel particle images. The optimum seeding density range was wider with lower velocity variation, as would be expected. The simulation implies that a seeding density in the range 3-10% is most likely to give good correlations. The Keane and Adrian (1990) criterion stated in Section 2.4.4.4 of a minimum of 15 particles per interrogation region would have corresponded to a 1 % seeding density in this calculation, i.e. the result is compatible with this criterion. They did not report a maximum seeding density beyond which noise correlations could become too significant.



These optimum values were deduced using simulated data. The particle images were single pixels, the seeding density was uniform and the velocity variations were controlled. Therefore, the values could only be a very rough guide and investigation of experimental images was required to give guidelines that could be used with confidence.

3.2.6 Summary of simulations.

As a result of the simulations, a preferred strategy for performing DPIV began to emerge. It was clear that the seeding density was an important factor. The sampling was chosen with no overlap of adjacent interrogation regions. The ability to choose region sizes of any integer number of pixels was important. Consequently, to reduce noise, a direct numerical algorithm was introduced. This was speed optimised, debugged and tested on the simulated images.

3.3 Experimental images : uniform flow.

Experimental DPIV images were obtained from a simple application to test the analysis system and develop the implementation of the technique. Initially an application was chosen that would give a near uniform velocity, in order to demonstrate DPIV at its most basic level.

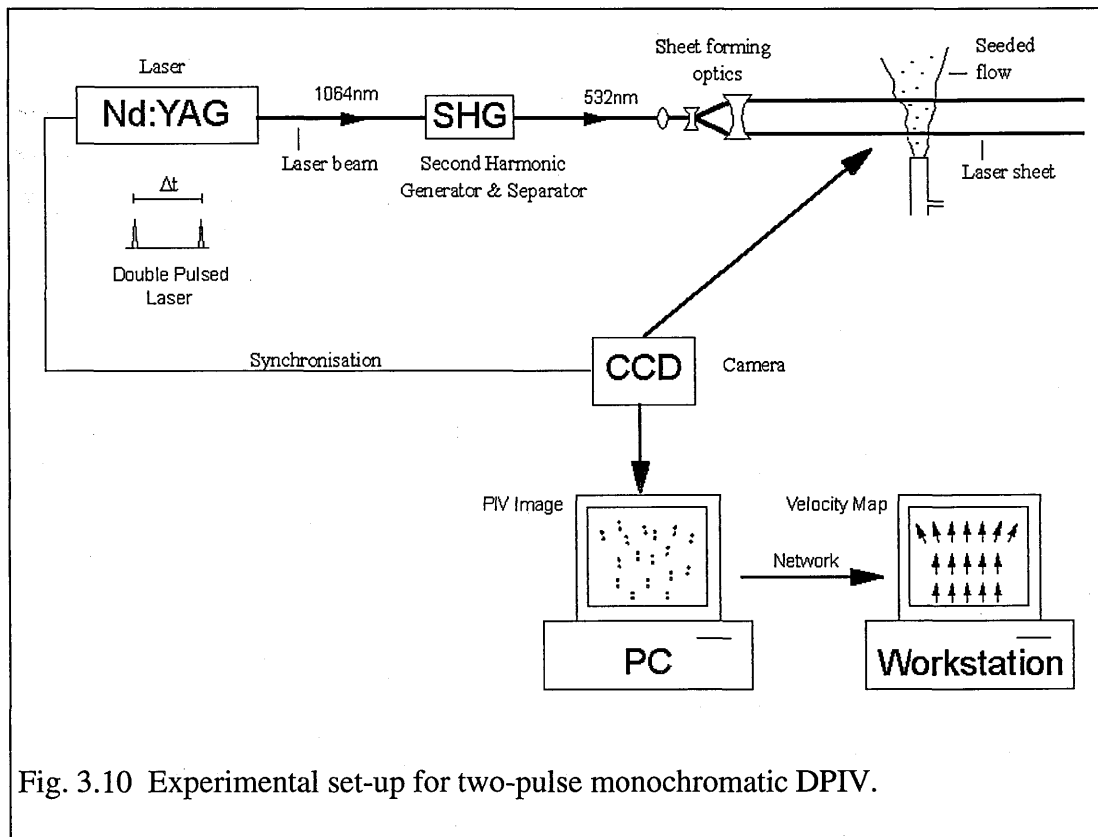


Fig. 3.10 Experimental set-up for two-pulse monochromatic DPIV.

3.3.1 Apparatus.

The experimental set-up is shown in Fig. 3.10. The laser was a Continuum Surelite I, with a double Marx bank to allow two pulses within an envelope of 20-200 μ s, with one pulse envelope every 100 ms (rep. rate = 10 Hz). A Second Harmonic Generator (KD*P crystal) doubled the frequency of the fundamental infra-red (1064 nm) laser output to 532nm, which is in the green region of the visible spectrum. The laser beam had a gaussian profile, with a diameter (FWHM) of 3 mm, pulse duration 5-7 ns and energy up to 180 mJ per pulse at 532nm, depending on the pulse separation.

The laser beam was formed into a sheet of minimum waist 1 mm, height approximately 50 mm, using a combination of a f+1500 mm spherical lens and f-12.7 mm, f+50 mm cylindrical lenses, forming a Galilean telescope.

The CCD camera used was a Wright Instruments air cooled, slow-scan, 15-bit, monochrome camera, with an array of size 600 x 400 pixels. A Nikon f2.8, focal length 60 mm macro lens was used, allowing a magnification ratio up to 1:1. The use of a 532 nm bandpass filter in front of the imaging lens allowed an exposure time of up to 20 ms, without ambient light causing background signal on the DPIV images. This exposure time allowed the mechanical shutter to open (2-5 ms) and the Mie scattered light from one laser envelope to fall on the CCD array. The shutter was synchronised with the laser, using the camera control software and a TTL trigger signal from the laser. Images were taken with the camera perpendicular to the laser sheet, imaging an area of 15 x 10 mm to give a magnification factor of 1, pixel resolution 25 μm and spatial resolution 50 μm .

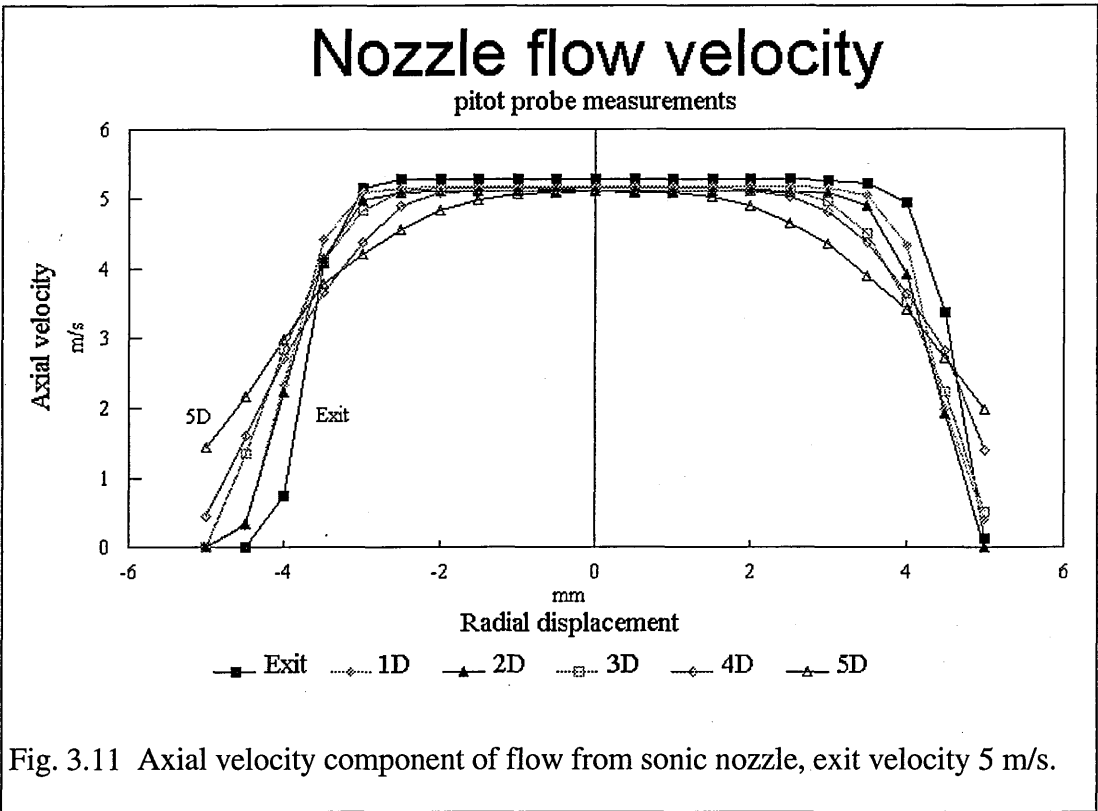


Fig. 3.11 Axial velocity component of flow from sonic nozzle, exit velocity 5 m/s.

A sonic nozzle (exit diameter 8 mm) was used to provide the flow. The air flow had a very low flow rate, to produce a flow which was laminar in the centre, with turbulence (eddies) at the edges. The flow was seeded with water, using a TSI 9302 atomizer, which produced droplets in the range 2-5 μm (see 2.4.4.1). This was introduced 100 mm upstream of the nozzle exit, sufficient to allow the whole flow to be uniformly seeded. The downstream velocity component was calibrated against the

supply air flow rate, using a pitot probe. Fig. 3.11 shows the downstream velocity component profile for an exit velocity of 5 m/s. Traverses were made at six different locations, from the exit plane to 5 diameters downstream.

3.3.2 Analysis.

DPIV images were taken with different flow rates, seeding densities and pulse separations. Some of these sets were not useful, for example because the displacement between particle image pairs was too large, compared with the image size, or the seed was badly distributed.

Fig. 3.12a shows an example of a good image. The white dots are seed particle images. The nozzle exit was at the bottom of the image, with the flow direction from the bottom to the top. The flow has a width of 8 mm (the nozzle exit diameter), broadening slightly further downstream. Fig. 3.12b show the best velocity vector map produced from this image. It had an interrogation region size of 80 pixels, giving the vector map resolution as 2 mm. The vectors are quite uniform, though there are only 5 x 7 regions. The graphs in Fig. 3.11 for exit plane and 1D (8 mm) downstream show that the velocity is very uniform in this region. It would have been a good idea to image further downstream, e.g. 4D to compare the data. A better comparison would have been to map the less uniform region with an LDA system.

A larger area (1311 x 1037 pixels) version of the Wright Instruments CCD camera was used to take further DPIV images. Fig. 3.13a shows a good image from the same flow, this time imaging 13.2 x 10.5 mm, magnification factor 1.5, pixel resolution 10 μm , optical resolution 30 μm . Fig. 3.13b shows a velocity vector map of this image, with interrogation region size 50 pixels, giving a vector map resolution of 500 μm . The larger chip array allows a more detailed vector map and a finer spatial resolution. most of the vectors are uniform, with some exceptions at the edges of the flow or regions with low seeding density. With such a vector map, spurious vectors could easily be corrected with interpolation (see 4.4.10).

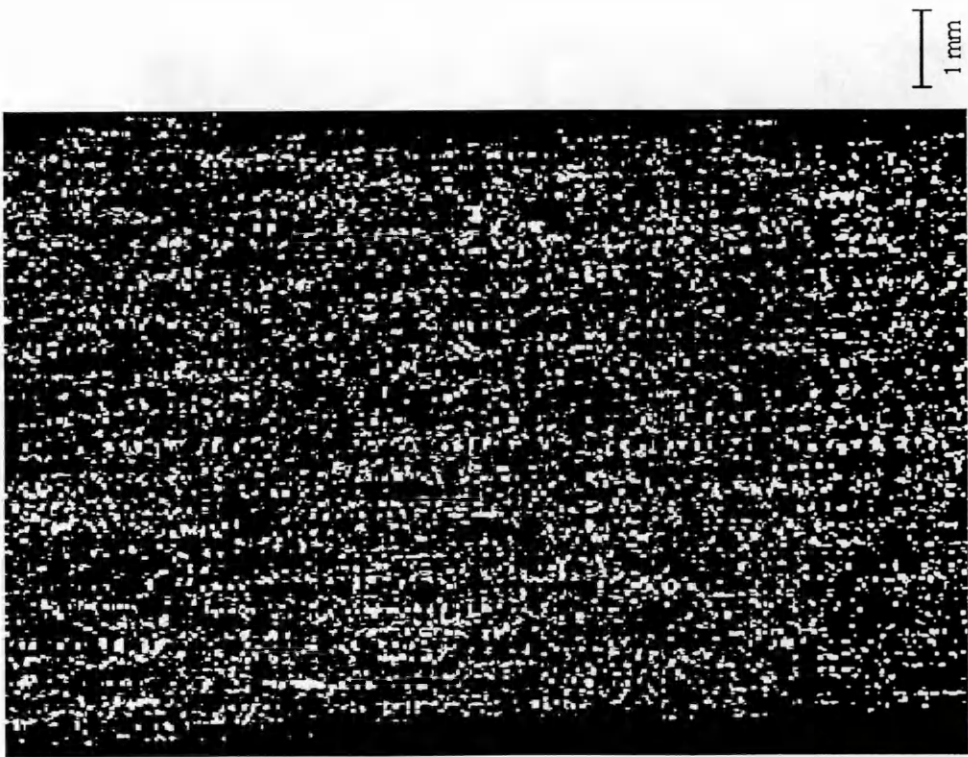


Fig. 3.12a Experimental DPIV image of flow from sonic nozzle.

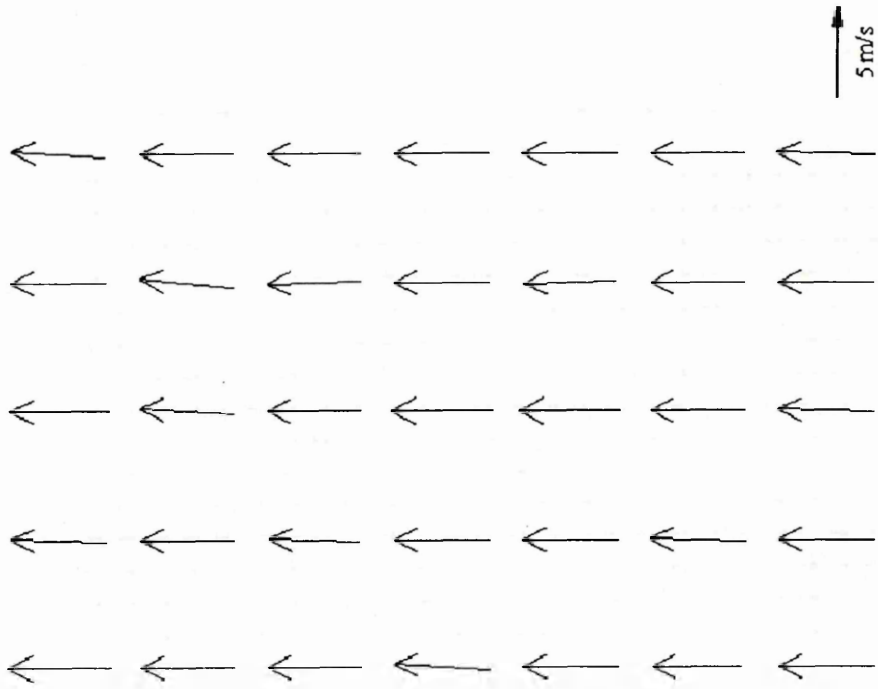


Fig. 3.12b Velocity vector map of image in Fig. 3.12a.

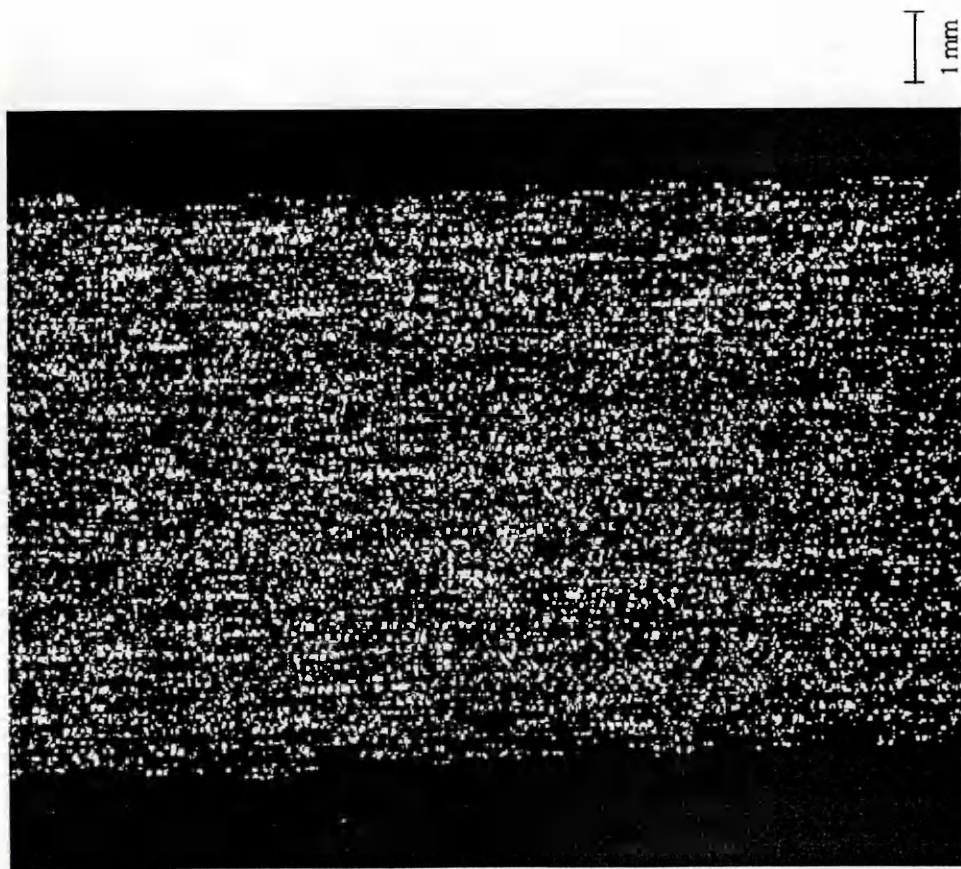


Fig. 3.13a DPIV image taken with the large area CCD camera.

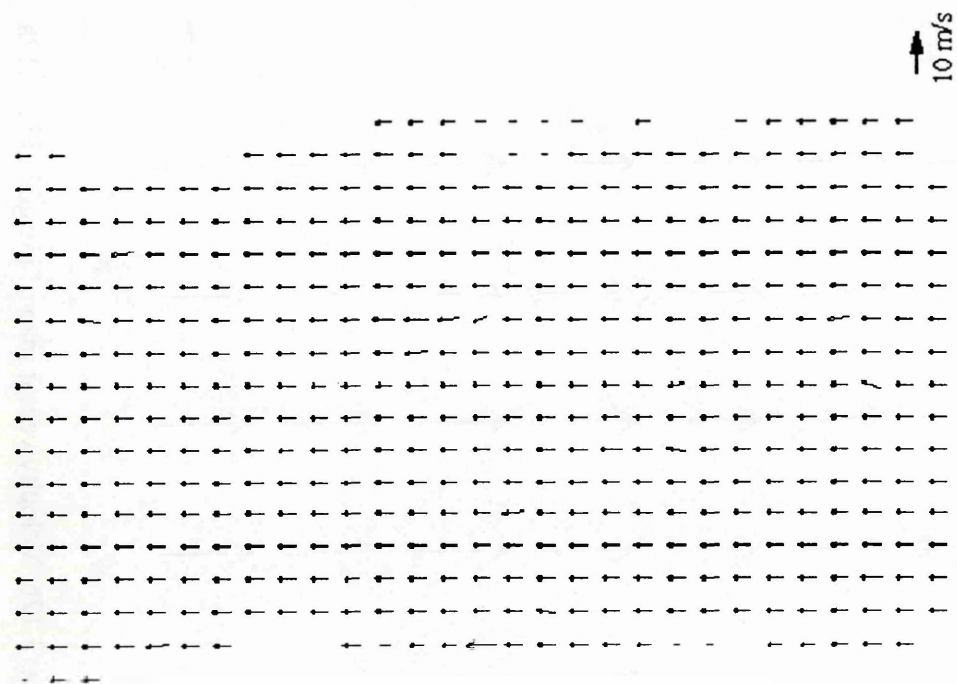


Fig. 3.13b Velocity vector map of image in Fig. 3.13a.

3.4 Experimental images : non-uniform flow.

The next stage was to attempt to make measurements on non-uniform flows. This would be important when considering turbulent flow fields in the vicinity of premixed flames. The basic assumption in correlating an interrogation region is that the local velocity of particles in the region is uniform. In a near-uniform velocity flow, this condition is easily achieved. When taking DPIV images of non-uniform flows, the choice of interrogation region size must attempt to fulfil this condition.

In addition to the ability to extract vectors with good signal to noise ratios from images of non-uniform flows, the feature of directional ambiguity in monochromatic two-pulse PIV becomes important when the flow direction is not previously known. For example, if a PIV image were intended to measure the strain at a turbulent flame-front, the velocity direction would determine the sign of the strain. It would be important to know whether adjacent areas of a flame-front experienced strain of the same, or opposite sign.

Fig. 3.14a shows an image taken from the flow through a Coanda nozzle, a low pressure, high volume nozzle. A bluff body was placed downstream to create regions of turbulence, and the region immediately downstream of the bluff body was imaged.

Fig. 3.14b shows the best velocity vector map that was achieved with the two-pulse analysis software. It is clear that a high proportion of vectors are unlikely to truly reflect the local flow velocity. Where the velocity appears to be correct, there is doubt whether the sign of the direction has been resolved correctly.

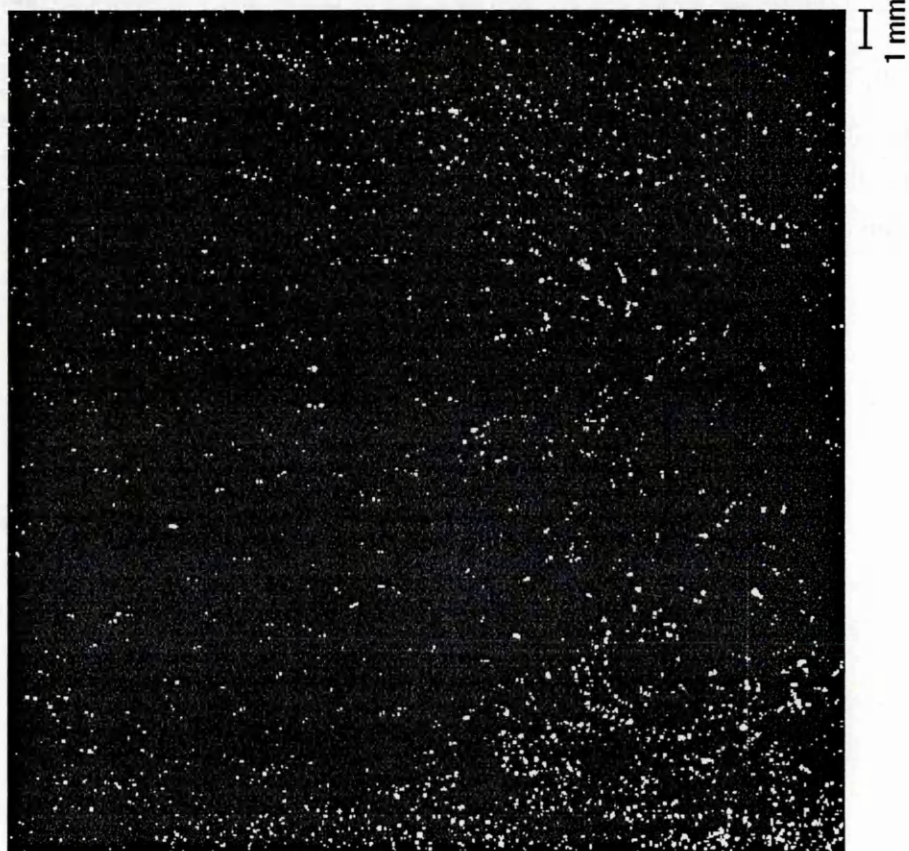


Fig. 3.14a DPIV image from non-uniform flow.

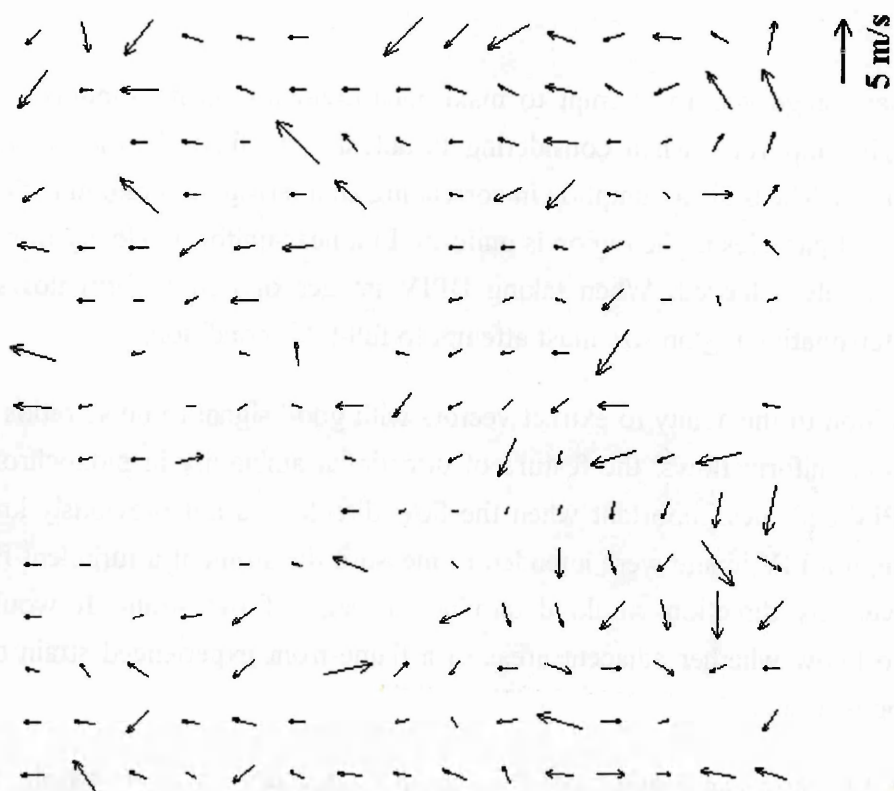


Fig. 3.14b Velocity vector map of image in Fig. 3.14a.

3.5 Summary.

A computer simulation generated sample DPIV data, which was analysed using software written "in-house". The best analysis appeared to require non-overlapping interrogation regions, whose size could be any integer number of pixels. Initially, FFT algorithms were used, but these were replaced with a direct numerical calculation due to noise in the autocorrelation function created by padding of the interrogation region. From the simulations, optimum parameters were deduced for seeding levels and interrogation region sizes.

Two-pulse DPIV was successfully applied to uniform experimental flows, to give good quality velocity vector maps. A small digital array of size 600 x 400 pixels proved to be restrictive in terms of the quality and usefulness of DPIV images. A larger array of size 1037 x 1311 pixels allowed the imaging of a larger region, with a greater spatial resolution.

When non-uniform flows were imaged, the analysis produced some correlation functions with low signal to noise ratios, resulting in several "bad" velocity vectors in the vector map. The sign of the direction of an extracted velocity was not known using this monochromatic two-pulse variation of PIV. Since this feature would cause significant problems when attempting to measure turbulent flows in a combustion environment, a method which provided directional resolution was required. Chapter 4 describes the development of a three pulse technique that provided this feature.

Chapter 4.

Development of a new variant of PIV : Three Pulse DPIV.

4.1 Introduction.

Chapter 3 described the investigation of two pulse monochromatic DPIV. It showed that for uniform flows, the technique could produce high quality velocity vector maps. However, when the velocity field was non-uniform, the technique was unable to show the sign of the flow direction and vector drop-out increased due to increased noise in the autocorrelation functions..

The ability to resolve the flow direction unambiguously would be very important in applying PIV to a wider range of flows, particularly turbulent combusting flows, where the velocity could be expected to fluctuate significantly. Without this feature, PIV would not become a general combustion diagnostic, but would be limited to particular combustion geometries where the flow direction was known *a priori*.

In order to address this issue, the potential of a multi-pulse monochromatic technique was investigated. In principle, multi-pulse methods allow the flow direction to be coded into the DPIV image (see 2.3.5). The use of additional monochromatic laser pulses with single frame imaging is intrinsically less complicated than other methods of resolving the sign of the velocity (see Section 2.3).

This chapter describes the development of a new variant of DPIV, which used a third monochromatic laser pulse to resolve the direction of flow and improve the signal to noise ratio in the correlation function using, a triple-correlation function. Experimental images were taken from non-uniform flows, such as in a counterflow burner, in order to demonstrate the technique.

The algorithm for performing the triple-correlation function was not available from commercial PIV analysis packages, which tend to restrict the user to pre-defined methods and parameter ranges. Consequently, analysis software was written to extract the velocity maps from Three Pulse DPIV images. Section 4.4 describes the principles of this software in detail, including various algorithms for maximising the data extracted from each image.

4.2 Three pulse digital particle image velocimetry.

4.2.1 Technique.

Three Pulse DPIV (Farrugia et. al., 1995) is a very straightforward extension to the standard two pulse monochromatic method. A third laser pulse is introduced, with unequal temporal spacing between the three laser pulses, so that there are three images of each seed particle in the Three Pulse DPIV image, forming a *triplet*. This is shown in Fig. 4.1, where A, B and C are the images of a single seed particle due to laser pulses 1, 2 and 3 respectively. The relative spacing in the image is equal to the relative pulse separation. For this work, the shorter separation was between the first and second laser pulses, so the flow direction for an image triplet was known unambiguously to be from the shorter to the longer displacement.

This three pulse variation has several potential advantages over others:

- a monochromatic CCD camera is sufficient,
- the whole camera array is used; there is no loss of image resolution,
- there are no alignment difficulties, including restorative transformation, that are encountered with multi camera methods,
- the pulsed lasers that are used give high signal point images compared with c.w. lasers,

• an additional Nd:YAG laser is easier to incorporate into an experimental set-up than a dye or c.w. laser.

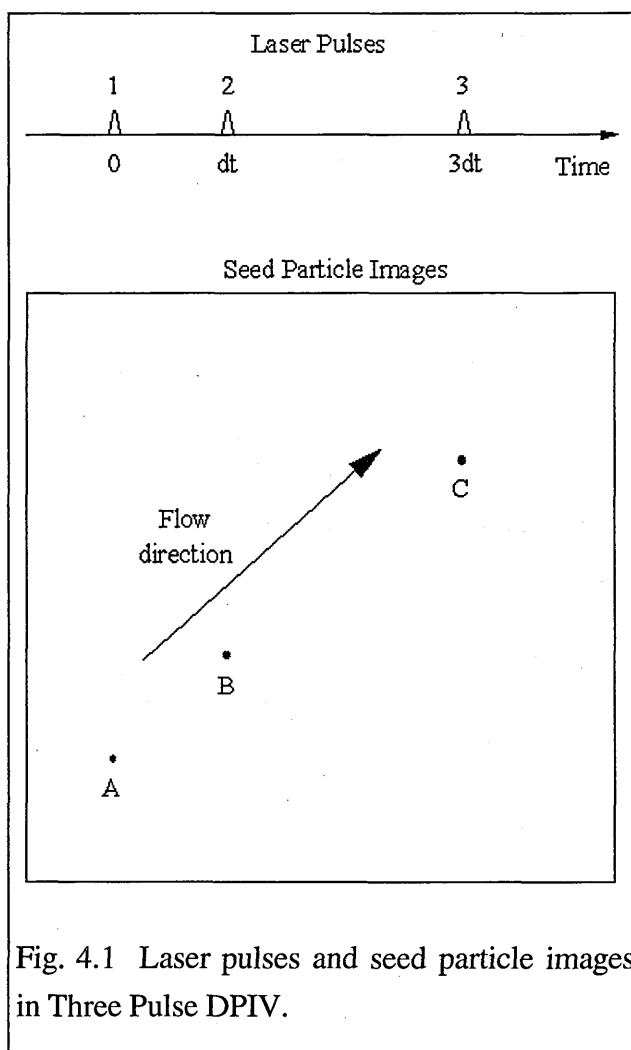


Fig. 4.1 Laser pulses and seed particle images in Three Pulse DPIV.

4.2.2 Relative pulse separation.

The relative pulse separation n can be defined as :

$$n = \frac{\Delta t_{(1 \rightarrow 3)}}{\Delta t_{(1 \rightarrow 2)}}, \quad n > 2.0 \quad (4.1)$$

where $\Delta t_{(1 \rightarrow 3)}$ is the temporal separation between the first and third laser pulses and $\Delta t_{(1 \rightarrow 2)}$ is the separation between the first and second laser pulses.

If n is small (in the range 2.0 - 3.0), the different displacements in the image triplet may not be sufficiently distinct for the analysis software to distinguish them; for $n = 2.0$, the spacing is equal and no directional information is present. As n becomes large, the different displacements become more distinct, but the duration of the pulse envelope increases, and may exceed the range of the laser equipment. More importantly, the distance on the image covered by an image triplet increases, which reduces the velocity range that can be resolved and also increases the likelihood that correlations will be lost due to small accelerations, i.e. the three images in a triplet will be less likely to lie in a straight line. Throughout this work, a compromise value of relative pulse separation $n = 3.0$ was used, i.e. a displacement spacing of 1:2. This was chosen intuitively, though a detailed investigation of whether it is the best theoretical value would be useful.

4.2.3 Autocorrelation function.

Analysing a three pulse image using an autocorrelation function would produce many signal peaks, corresponding to each pair of seeding particle images within the image triplet (Fig. 4.2). The number of particle pair combinations would be $3^2 = 9$, of which seven would be distinct. The extraction routine could distinguish these peaks and deduce the velocity for the interrogation region, but this would not be the optimum strategy for three reasons :

- it is unlikely that a good set of peaks would always be present in the autocorrelation function.
- the autocorrelation function would have to be larger, to contain all the peaks,

- an autocorrelation function cannot provide directional resolution. The analysis routine would have to revisit the original image to determine the flow direction.

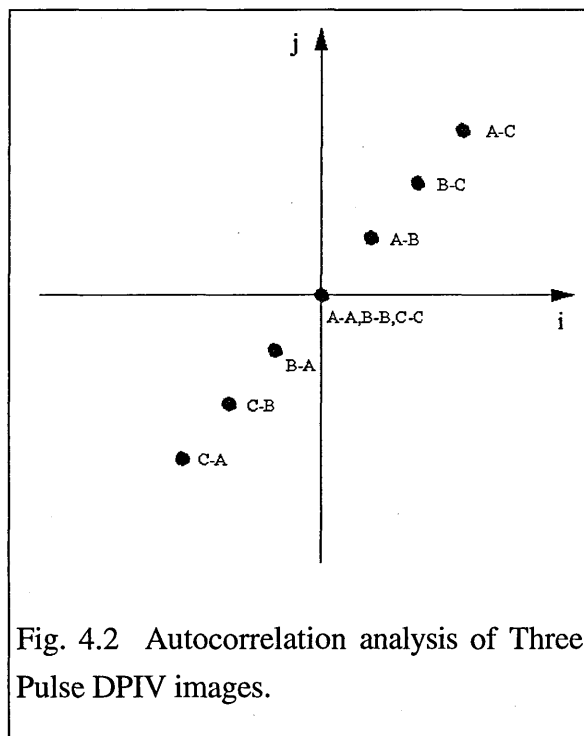


Fig. 4.2 Autocorrelation analysis of Three Pulse DPIV images.

4.2.4 Triple-correlation function.

In order to extract the direction information when analysing a Three Pulse DPIV image, another term was added to the autocorrelation function, to produce a **"triple-correlation function"** :

$$T(i, j) = \sum_{x,y} [S(x, y) \cdot S(x + i, y + j) \cdot S(x + ni, y + nj)] \quad (4.2)$$

The third term causes correlations to occur only for triplets of seeding particle images with the correct relative spacing, so the flow direction is extracted directly. The number of noise correlations between images of different seeding particles is greatly reduced, since it is far less likely that there will be multiple sets of triplets of such particle images.

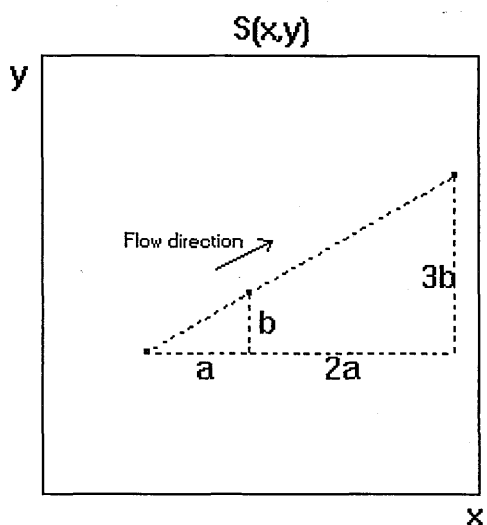


Fig. 4.3a Interrogation region with a single image triplet.

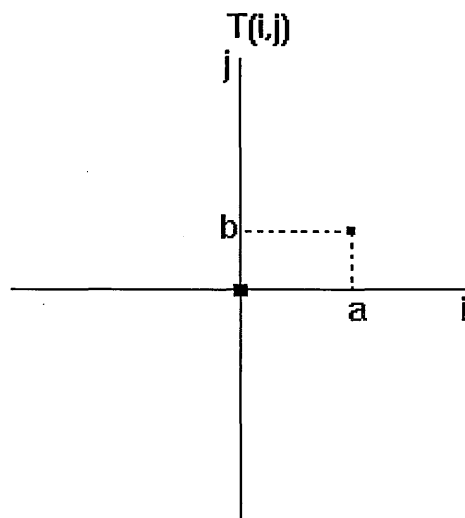


Fig. 4.3b Triple-correlation function of region in Fig. 3.4a.

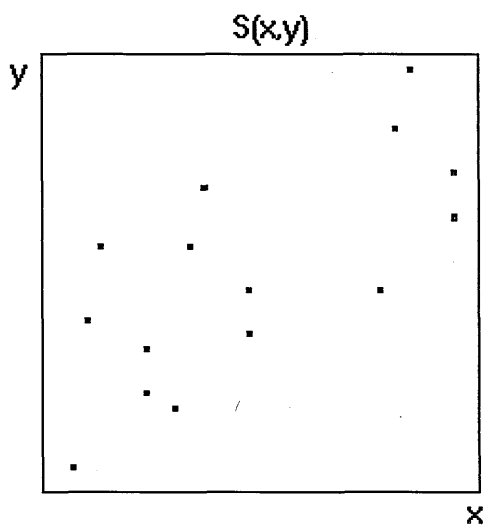


Fig. 4.3c Interrogation region with many image triplets.

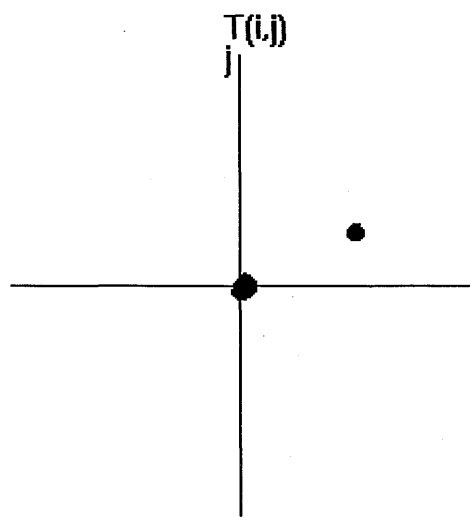


Fig. 4.3d Triple-correlation function of region in Fig. 4.3c.

Fig. 4.3a shows a single image triplet in an interrogation region. The corresponding triple-correlation function shown in Fig. 4.3b contains a peak for zero displacement and only one signal peak, corresponding to the velocity in the correct direction. For an interrogation region with many image triplets (Fig. 4.3c), the triple-correlation function (Fig. 4.3d) has a reinforced signal peak, but no noise peaks. This is because in this example there are no sets of three particle images from *different* particles that lie in a straight line *and* have the correct relative spacing.

It should be noted that the three pulse, triple correlation combination does not allow zero velocities to be measured due to the presence of the self correlation peak, i.e. particle images from different laser pulses at the same location cannot be resolved. The increase in pulse envelope length reduces the velocity bandwidth and makes the chances of a correlation more susceptible to variations of velocity in a region.

"Three Pulse DPIV", as the combination of generating three unequally spaced particle images from pulsed lasers, with the triple-correlation function and the completely digital process from image capture to velocity vector map display is a novel variation to PIV. To December 1995, no other reference to such a technique was found in the literature.

4.2.5 Apparatus.

The implementation of Three Pulse DPIV required a very modest upgrade of the experimental apparatus used for two pulse DPIV in Chapter 3. Once three laser pulses were produced within the required time envelope using an additional Nd:YAG laser, the same camera system could be used to capture the images, though a small CCD array would have been more restrictive than it was with two pulse DPIV, due to the increased pulse envelope.

One way of producing three short laser pulses with specified relative spacing would be to chop the output of a continuous wave laser, such as an argon ion laser. This would have two drawbacks, discussed in Section 2.4.5.1:

- there would be a requirement for either a mechanical chopper or a fast camera gate,
- the particle images would have much lower intensity than with a pulsed laser and might have a tendency to blur.

It is uncommon to have a pulsed laser system that can give three pulses within one pulse envelope. The system that was used incorporated the existing double-pulsed Nd:YAG laser (see 3.3.1), with the addition of another, single pulsed Nd:YAG laser. This was a Continuum Surelite II, which produced up to 350 mJ per pulse at 532 nm.

The experimental set-up is shown in Fig. 4.4. The infra-red beams from the two lasers were combined, using a 45° mirror, a half-wave plate to rotate the polarisation of one beam and a polarisation beam-splitter to make the two beams co-linear. The beams were then sent through the SHG, wavelength separator, telescope and sheet-forming optics that were used for the two-pulse method. Thus, with two pulses from the Surelite I and one pulse from the Surelite II, three laser pulses could be delivered to the flow.

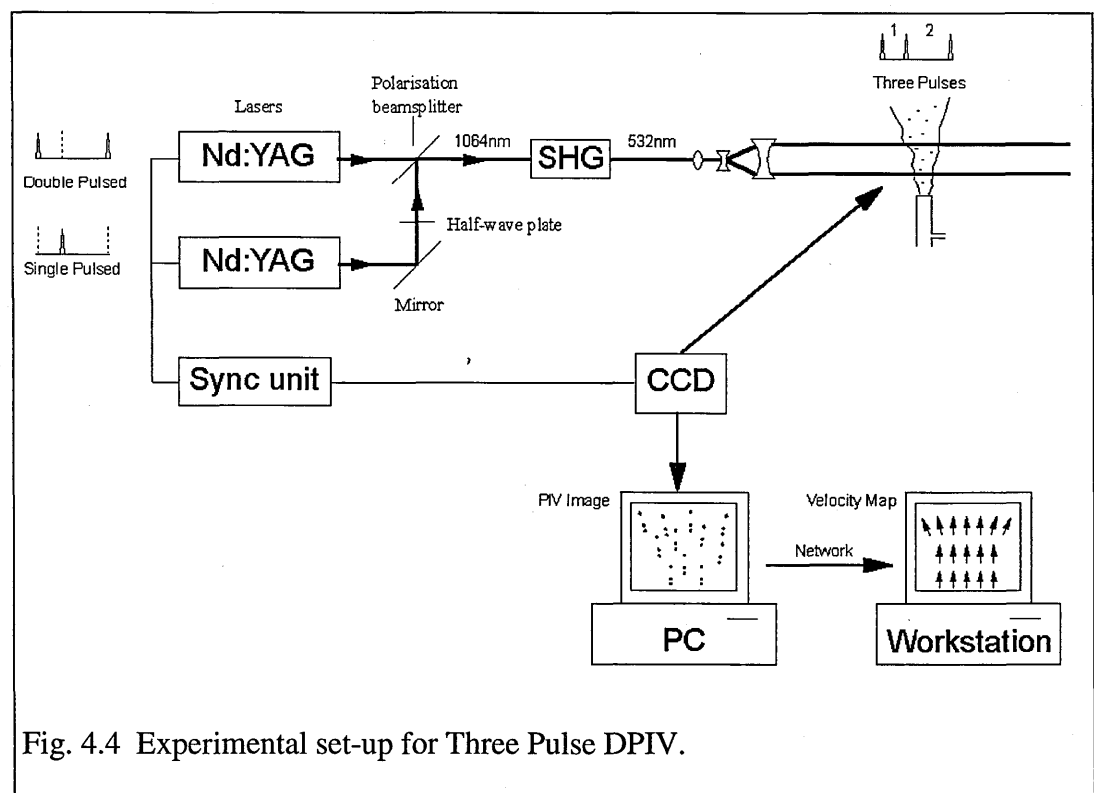


Fig. 4.4 Experimental set-up for Three Pulse DPIV.

4.2.6 Pulse envelope.

Since two separate lasers were used, it was necessary to externally trigger both flashlamps and Q-switches, to ensure that the three pulses were generated within the required envelope and with controllable time separations. A synchronisation unit (Continuum DL100) with an internal 10 Hz clock was used.

There were two distinct ways of arranging the sequence of three laser pulses, illustrated in Fig. 4.5 :

- a) Surelite I:pulse 1 - Surelite I:pulse 2 - Surelite II.
- b) Surelite I:pulse 1 - Surelite II - Surelite I:pulse 2.

The choice of pulse order depended on the pulse envelope, which was adjusted to match the average flow velocity and image magnification factor. Combination a) gave the maximum pulse envelope. With $n = 3.0$, and Surelite I double-pulse maximum separation of $200\ \mu\text{s}$, this could be up to $600\ \mu\text{s}$. Combination b) gave the minimum pulse envelope, determined by the double-pulse minimum separation of $20\ \mu\text{s}$.

The pulse separations and relative energies were monitored with a fast photodiode. Pulses of equal energy were preferred in order that each seed particle image in a triplet would have a similar intensity level (see 4.4.3).

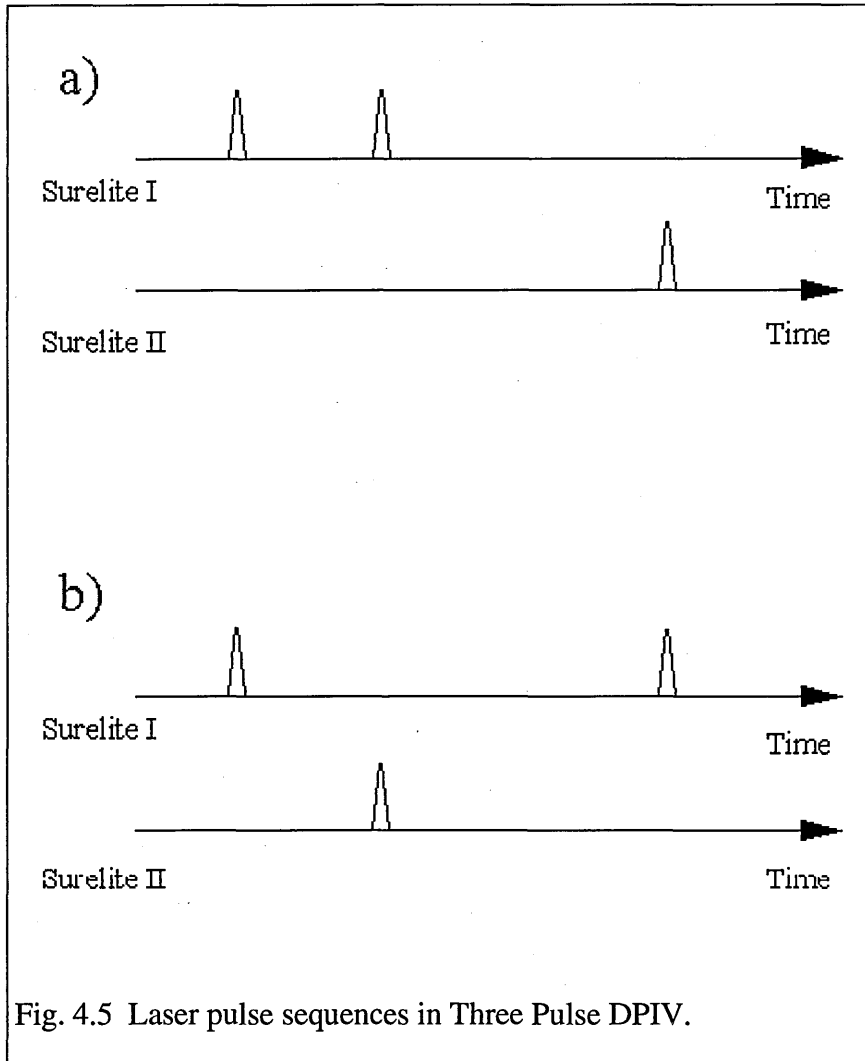


Fig. 4.5 Laser pulse sequences in Three Pulse DPIV.

4.3 Experimental DPIV images.

4.3.1 Uniform flow images.

To test the new technique on straightforward data, and to fine tune the set-up of the apparatus, some images were taken from a simple nozzle, the same uniform flow that was used for the initial two-pulse images in Section 3.3. The camera imaged a region of size 10 x 13 mm immediately downstream of the nozzle exit, with the air velocity set to approximately 5 m/s.

Four sets of twenty images were taken, with different seeding densities, camera settings and pulse separations. This was the standard initial experiment to determine the optimum experimental parameters. An example of an image with the best conditions is shown in Fig. 4.6a, with the corresponding velocity vector map in Fig. 4.6b. It is clear that the flow velocity in the plane of the laser sheet was well resolved.

4.3.2 Non-uniform flow images.

Some images were taken of the cold flow in the Cranfield counterflow burner, which is described in more detail in Chapter 7. This consisted of two opposing, balanced air flows, with a stagnation plane in the middle. The flow was seeded on both sides with TiO_2 particles (2 μm diameter) and several datasets were taken with different conditions.

Fig. 4.7a shows an example Three Pulse DPIV image, where the nozzle separation was 23 mm, with exit velocities of approximately 10 m/s. The laser pulse separations were 33.3 μs and 100.0 μs , with a magnification factor 1.67. Fig. 4.7b shows the velocity vector map produced by the fully optimised triple-correlation analysis software, described in Section 4.4. Along the centreline of the nozzles, the velocity decreases from 2.3 m/s at the left hand edge of the image, to zero at the stagnation plane, then increases in the opposite direction to 4.3m/s at the right hand edge of the image. The perpendicular velocity component increases from zero at the nozzle centreline (top) to 5.8 m/s at the bottom edge of the image. Each velocity vector has a 10% error, dominated by discretisation. This would be reduced by resolving to sub-pixel accuracy (see 4.4.8). This image and vector map illustrate the ability of the Three Pulse DPIV method to resolve the velocity direction, in a case where it was varying significantly throughout the image.

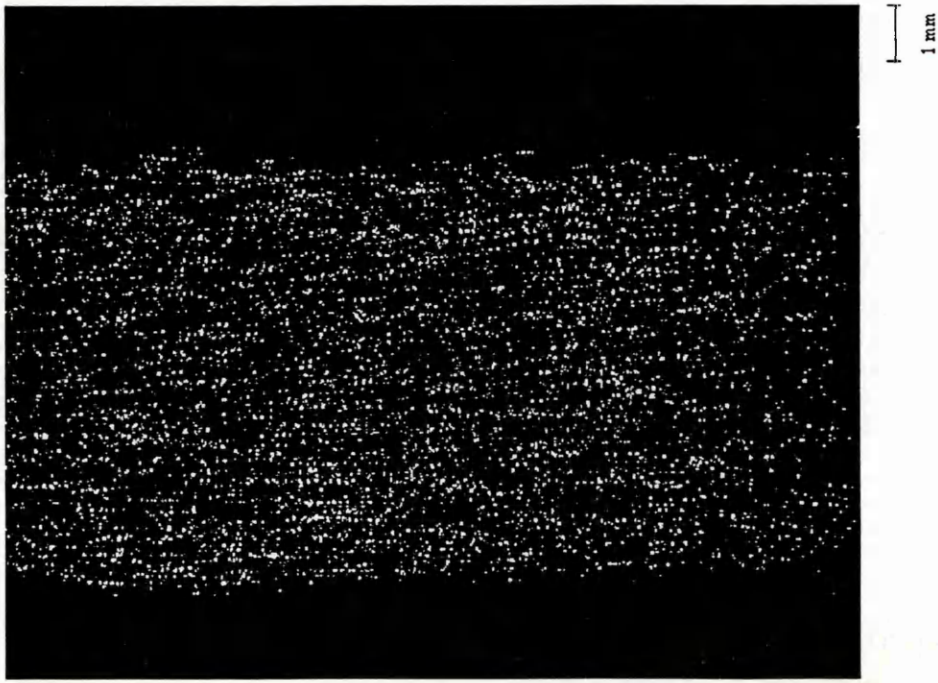


Fig. 4.6a Three Pulse DPIV image of a uniform flow from the sonic nozzle..

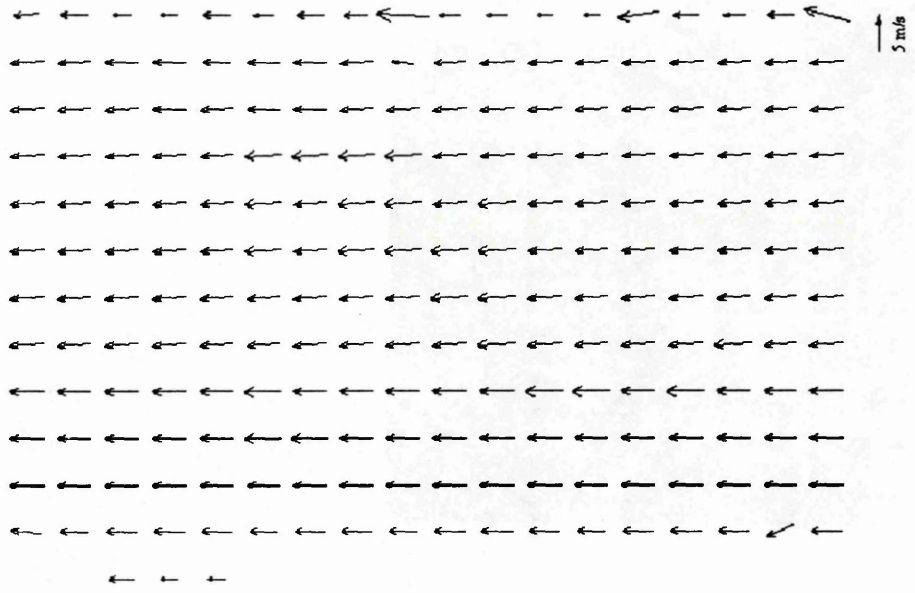


Fig. 4.6b Velocity vector map of image in Fig. 4.6a.

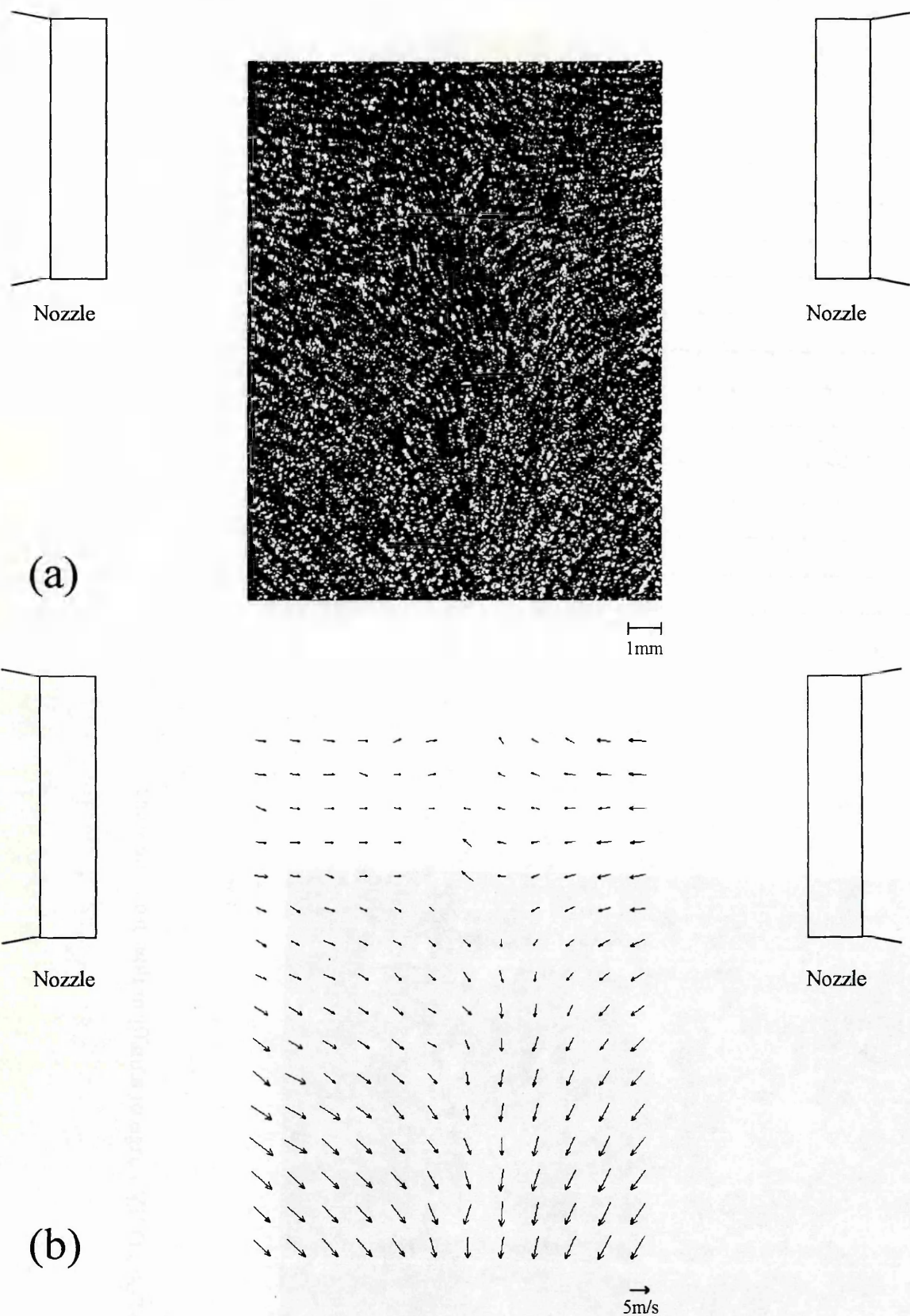


Fig. 4.7 (a) Example Three Pulse DPIV image of a flow from a counterflow burner, (b) velocity vector map of the image in (a).

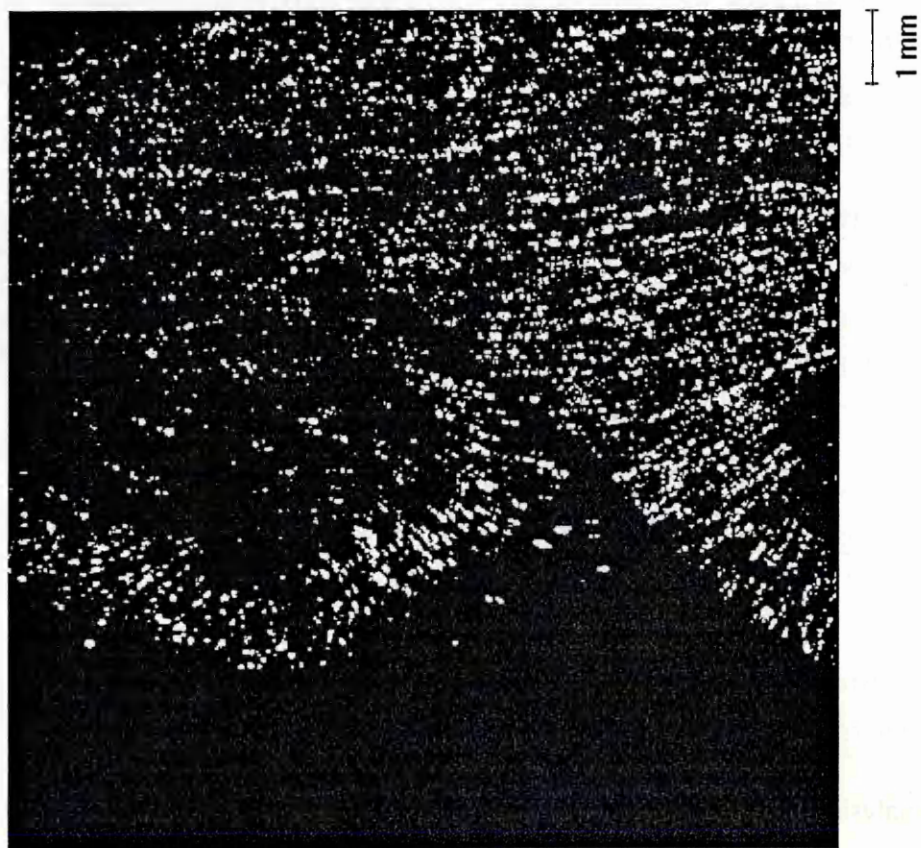


Fig. 4.8a Three Pulse DPIV image from the edge of the flow from the sonic nozzle.

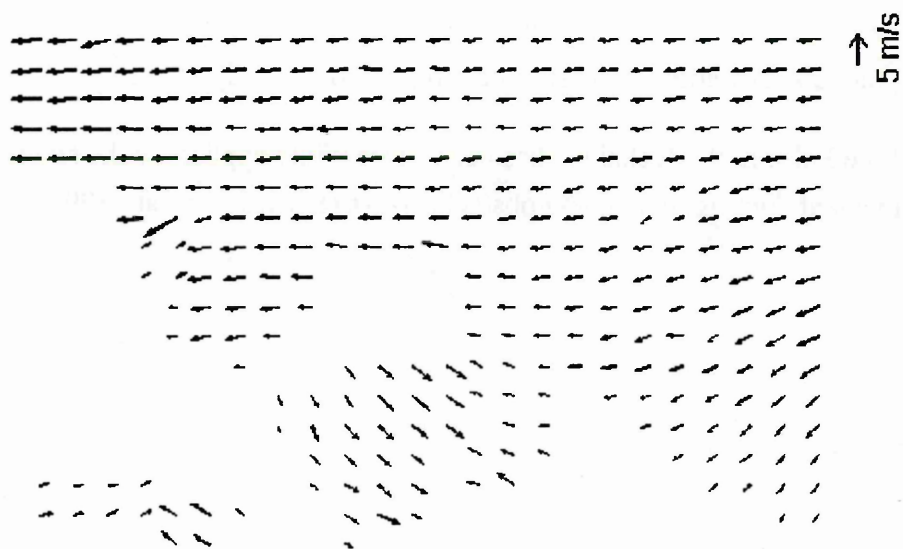


Fig. 4.8b Velocity vector map of image in Fig. 4.8a.

An example image of the non-uniform velocity field at the edge of the flow from the sonic nozzle (see 3.3.1) is shown in Fig. 4.8a. The best velocity vector map of this image, using the fully developed analysis software, is shown in Fig. 4.8b.

The Three Pulse DPIV technique has been successfully applied by the sponsor to the flow in a vented duct rig, containing obstacle arrays (Snowdon et. al., 1996).

4.4 Analysis Software.

4.4.1 Custom written software.

Generating experimental DPIV images was a relatively straightforward procedure. The most difficult aspect was producing an appropriate uniform density of seeding particles in the measurement region. Once the experimental conditions were optimised, a large dataset of images could be recorded rapidly. The majority of work in developing and implementing the Three Pulse DPIV system involved investigating, writing and testing the analysis procedure in order to extract the maximum amount of useful velocity data from the images.

The initial two-pulse DPIV images were analysed using the FFT routines in the "CLIPS" suite, written and developed at Cranfield University by N. P. Tait. This software could read and write images in a variety of formats. It could perform simple arithmetic functions on images, e.g. addition, square-rooting as well as more complex functions such as masking or Fast Fourier Transforms.

When it was decided to move to the non-Fourier Transform analysis (see 3.2.4), a standalone program was written. An "in-house" program was written in order to incorporate novel analysis variations that were not available from commercial codes, for example the triple-correlation function or different centroiding functions. The flexibility of custom written software allowed the technique to be investigated in a thorough manner.

The analysis software was written in C to run on Digital DEC and Alpha workstations, which had a UNIX operating system and an XWindows front end. It was

translated into Borland Turbo C++ (version 3.1) for use on DOS based PCs with a Microsoft Windows v.3.1 front end. This allowed immediate analysis of PIV images, so that experimental conditions could be optimised interactively and it allowed analysis of complete experimental sets to be performed when workstations were not available, e.g. whilst at the sponsor's laboratories.

The general structure of the algorithm was :

1. The image was loaded into memory from file "filename", along with the parameters to be used for the analysis e.g. size of interrogation region.
2. One interrogation region was processed at a time. These were adjacent square areas of the DPIV image of a pre-determined size, N .
3. The correlation function of the interrogation region was produced. This could be an autocorrelation function for two pulse DPIV or a triple-correlation function for Three Pulse DPIV.
4. The highest non-zero peak in the correlation function was extracted. If it possessed a signal to noise ratio above the validation criterion, its displacement was converted into a velocity vector for that region of the image. Otherwise, the region was given no velocity vector.
5. The values for the velocity vector map of the whole image were written to a file.
6. Any post-processing was carried out and the results written to another file.

4.4.2 Complexity of analysis.

In constructing the analysis algorithm for PIV images, a balance was required between the conflicting factors of the accuracy and the speed of the analysis. In aiming to extract the maximum possible number of correct velocity vectors from each image, there are many processes that can be applied both before and after the correlation routine. However, each further process adds to the computation time, when it is often desirable to obtain the velocity data as quickly as possible. When a large data set is taken, it can be acceptable to perform the analysis overnight, but a vector map generation time in the range 1-5 minutes is necessary for optimising experimental parameters, particularly when the flow application is expensive to run.

Commercial PIV packages have tended to concentrate on providing a speedy, fairly straightforward analysis. Many can analyse images in near real-time, quoting analysis rates of order 10^4 vectors per second. When developing a technique, the limits of the technique are of interest; what kinds of flows it can be realistically applied to and what kind of accuracy can be achieved. New techniques compete with well established ones, and if PIV can give velocities to only 10% accuracy, while pointwise LDV can deliver 1%, it could prove difficult to promote PIV from being an interesting, qualitative method to a robust, quantitative technique which is the method of choice.

In investigating the variety of analysis procedures, there was always a judgement required of whether an increase of analysis time could be justified by an increase in accuracy. It was felt that the full analysis of an image in 5 minutes would be a reasonable rate. The final version of the software could analyse an average image in 3-5 minutes on a P90 PC, or 20-30 seconds on a DEC-Alpha workstation.

A further improvement in processing time could be achieved in using an FFT correlation algorithm to produce the triple-correlation function. It was not immediately clear how this could be achieved, so the programming concentrated on constructing a working direct numerical correlation procedure. The implementation of a Fourier analysis, if possible, would be an improvement, provided any increased noise due to padding (see 3.2.4) was not significant.

4.4.3 Particle image intensity.

The image of each seed particle in a DPIV image will have an intensity directly proportional to the amount of laser light scattered from that particle S , which is given by (Adrian, 1991) :

$$S = I_0 \int_{\Omega} \frac{\lambda^2 \sigma \cdot \sigma^*}{4\pi^2} d\Omega \quad (4.3)$$

where I_0 is the incident intensity, λ is the wavelength, σ is the Mie scattering coefficient of the particle and Ω is the solid angle.

With the 15-bit CCD camera, intensities could be saved on a 32,768 level greyscale. In practice, most images consisted of a background of approximately 150 counts and a signal of approximately 1000 counts, due to the experimental parameters of laser power and camera aperture. The laser power was kept at the maximum, while the camera aperture was closed down to improve the focusing.

The scattering intensity from an individual seed particle depended on the particle size and the local laser power, which varied both across the height of the sheet and across the thickness of the sheet. A larger particle in the middle of the sheet would give a much higher signal than a smaller one that was only partially in the laser sheet. A relatively thick sheet (~1 mm) was used to lessen the effect of incomplete particle image sets due to out of plane motion (see 2.4.5.5). It was found that for a set of images of one particle, with equal laser pulse energies, the intensities of each image tended to be very similar. An attempt to utilise this feature could be made by attempting to correlate intensity as well as position (*c.f.* the intensity graded sheet described in Section 2.3.8).

The grey-scale intensity information could be retained when performing the correlation function, as implied by Eq. 3.1 and Eq. 4.2. The correlation function would reflect the strength of the scattering signal. Considering an ideal image, there would be two main advantages to retaining the greyscale values. Firstly, since a correlation between two particle images may be the product of, say 500 and 500 counts, each correlation might score 25000 counts in the correlation function. The additive effect of signal correlations would be large, so that the height of the true displacement peak corresponding to the actual flow velocity in the interrogation region would be very large compared with the noise. The second advantage would occur because most seeding particle images extend over some 4-5 pixels, with the highest signal nearest to the centre of gravity of the seed particle. In the correlation function, the overlap of correlations in the vicinity of the true displacement would be correspondingly weighted, which should result in a more accurate vector.

However, the use of greyscale correlations results in three severe disadvantages. The correlation will be biased toward seeding particle images with higher intensities, which are usually larger particles which are less likely to follow the flow velocity faithfully. Secondly, a particle with a high intensity will contribute large noise correlations with all other seeding particle images in the interrogation region. A large particle entering or leaving the sheet during the pulse envelope would contribute only large noise correlations to the correlation function. One rogue particle image might prevent the correct flow velocity from being extracted from an interrogation region.

The primary disadvantage of performing a greyscale correlation is that it is extremely costly in computational time.

4.4.4 Binarisation: optimum seeding density.

In view of the disadvantages of greyscale correlations, binarisation of the DPIV image was used in the analysis, which was described in Section 3.2.4.2. Each pixel effectively took a value which was either unity or zero, determined by a binarisation threshold which was called **lo**. The value of **lo** had to be above the background level (typically 150-300 counts). Raising the value of **lo** further reduced the number of seed particle images included in the analysis, i.e. the effective seeding particle density ρ_{eff} .

In a particular image, the background level or the seed density might be too high in a particular interrogation region. If there are too many image pixels, the noise can become significant in a correlation function. A procedure was introduced which varied the threshold until the effective seeding density fell within predetermined optimum values, **smin** and **smax**. It progressively excluded particle images with lower intensities until the required effective seeding density was achieved.

The routine began at a lowest value for **lo**, termed **lo_start**. This was just above the background level. If ρ_{eff} were between **smin** and **smax**, the value **lo_start** was used as the binarisation threshold. If, for **lo** = **lo_start**, ρ_{eff} was below **smin**, the routine checked whether it was above **min_seed**, the minimum permitted seeding density. If that were the case, the correlation proceeded, using **lo_start** as the binarisation threshold value. If ρ_{eff} were below **min_seed**, there was insufficient signal in the interrogation region, so it was left blank. If ρ_{eff} were above **smax**, the value of **lo** was raised until ρ_{eff} lay within the desired range.

Since all the images of an individual seed particle usually had very similar signal intensities, raising the threshold tended to exclude whole image triplets, so the signal to noise ratio in the correlation function due to unpaired particle images was not affected. The procedure did bias the correlation toward the velocities of larger particles to some extent, but it was necessary in areas with very high seeding densities in the original PIV image, in order to allow the extraction of a velocity vector.

4.4.5 Particle image correlation.

Fourier correlation methods perform the correlation function on the whole interrogation region. The initial direct numerical algorithm, implementing Eq. 3.1 also performed the correlation on the whole interrogation region, i.e. N^2 pixels, requiring N^4 calculations. This was by far the largest use of CPU time ($> 90\%$).

The use of image position correlations was referred to in Section 3.2.4.3. Since only approximately 10% of pixels have an intensity above the binarisation threshold, most of the multiplications would be in effect calculating $0 \times 0 = 0$ and would thus be redundant. If the calculation included only the signal pixels, the number of calculations required might be of order $(N^2/10)^2$, a reduction to 1% of the previous number.

This method was implemented by creating an array of particle positions, i.e. pixels whose signal was above the binarisation threshold. For the triple-correlation function, the algorithm took all pairs of array elements and calculated their relative displacement. The theoretical position in the original DPIV image of the third particle image in the triplet was then calculated. If a particle image was found within one pixel of this position in the DPIV image, a count was added to the corresponding displacement peak in the triple-correlation function.

This method also removed self-correlations, i.e. zero displacement, which formed the highest peak in the conventional correlation function. Very small displacements (e.g. 1-5 pixels) remained, though they could not be considered as signal peaks since they lay within the possible size of a single particle image, i.e. they could be self-correlations. These correlations could have been excluded during the procedure, but instead were ignored in the peak extraction procedure (Section 4.4.7).

4.4.6 Interrogation region size.

The first parameter to be set in the analysis was the size of the interrogation region, denoted **reg**, which could be any integer number of pixels. Typically **reg** would vary from 50 to 150 pixels for a CCD array of size 1300 x 1000 pixels. (When CCD arrays attain the resolution of photographic film, the displacements and interrogation region sizes may be larger, allowing more accurate velocity maps.)

With a larger value of **reg**, there would be more seed particle images in the region, so the signal peak in the correlation function should be more distinct from the background noise. However, it would be less likely that the assumption of constant

velocity within the interrogation region would hold. In addition, the total number of velocity vectors, hence the resolution of the velocity map, would be reduced.

The opposite of these effects would occur if the interrogation region were smaller; there would be less seed particle images to correlate, the velocity would be more likely to be constant within the region, there would be more vectors in the map. The aim would be to find the smallest region size that produced good velocity data. A limiting case would occur when the size of the region approached the length of a seed particle image set. Then, the probability of having complete sets within the region would be very low. Willert and Gharib (1991) reported a minimum interrogation region size of three times the length of the image set.

4.4.7 Signal peak extraction.

When the correlation function had been generated, a routine to extract the common displacement for the interrogation region searched for the highest non-zero peak in the correlation function. The corresponding displacement could be converted into the velocity vector for that interrogation region. The analysis software repeated this procedure for each interrogation region to produce the "first pass" velocity vector map, writing the vectors to a file with the suffix ".raw".

With non-ideal data, the true signal peak might not be the highest in the correlation function (Keane and Adrian, 1990); there were fewer complete image sets than the largest noise signal from multiple random correlations. In order to improve the chances of finishing with as many correct vectors as possible, the peak extraction routine in the analysis software stored in memory a user-defined number, **npeak**, of peaks from each correlation function. If the post-correlation routine (see 4.4.9) rejected the first choice displacement, one of the alternative candidates could be chosen as the correct displacement.

In terms of validation criteria, the software used two parameters to determine whether a peak was acceptable as a possible signal peak. **min_sig** was an absolute minimum number of correlations required, typically 10-20. Unless a displacement vector occurred **min_sig** times in the interrogation region, it could not be considered a reliable value.

The other measure was whether the height of a peak was sufficiently large compared with the background noise peaks. Besides a few noise peaks with a high number of counts, most displacements would be at a background level. For a peak to

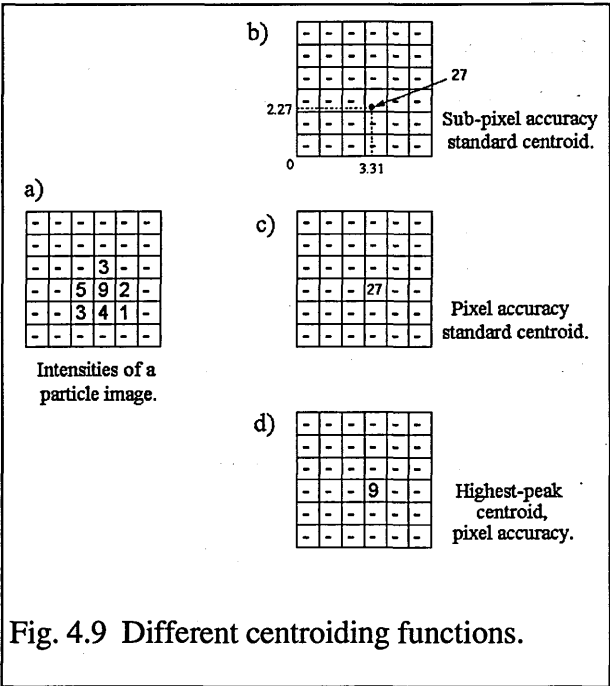
be considered as a candidate to represent the velocity in the region, it had to have a level above the background level by a factor **snr**, which might take a value such as 1.33. In order to perform this criterion automatically, the background noise level of the correlation function was chosen as the signal level at which the $(5 \cdot \text{npeak})$ th peak occurred.

It was an unavoidable feature of the search algorithm that peaks were chosen preferentially in a certain region of the correlation function. In two pulse PIV, with a symmetric autocorrelation function, both signal peaks would be extracted, but one would be encountered first in the search loop, so it would be first in the list of displacement candidates. The direction of this inherent bias could be chosen by the user, so that if a primary flow direction were known, the vector map would reflect it.

4.4.8 Centroiding.

Centroiding has often been used in optimising the data extracted from an image (Keane and Adrian, 1990; Guezennec and Kiritsis, 1990; Willert and Gharib, 1991). Performing a centroid function will reduce a feature extended over many pixels (Fig. 4.9a) to a single pixel (Fig. 4.9c), or even to sub-pixel accuracy (Fig. 4.9b). This will increase the resolution of the common displacement, thereby reducing the discretisation error (see 2.5.6.1). The most common centroiding function calculates the "centre of mass" of an object, perhaps weighted by the signal intensity at each pixel. Implementing this centroiding method would require an algorithm to identify the extent of an object before performing the centroid. Such an algorithm would be extremely complicated, particularly with a high seeding density where extended objects would be close together and often overlap.

A different form of centroiding was used in the analysis software, and was termed "highest peak centroiding". It was a simplified version of the standard method,



which assumed that within an extended object, the best pixel to represent the particle position would be that with the highest signal level. (With DPIV, seed particle images do not have unusual intensity gradients such as saddle points.) Each time the algorithm found a 3 x 3 set of pixels where the centre pixel had the highest signal, the set were replaced with just the central pixel, as shown in Fig. 4.9d. This method was very simple, but effective for the particular case of DPIV images.

There were two possible strategies for centroiding; centroiding the DPIV image, or centroiding the correlation function.

4.4.8.1 Centroiding the image.

A typical DPIV image, with optimum focusing, will contain many single pixel images of seed particles, but something like half of the images will extend over 3-4 pixels. This can be due to the resolution limitation of the optical system (see 2.4.9.1), the fact that scattered light may be incident at the boundary of CCD pixels, and possible "leakage" of charge to neighbouring pixels on the CCD chip.

Extended particle images in DPIV images cause the signal peak in the correlation function to become blurred, since additional correlations occur for displacements close to the true "flow displacement". Theoretically, if the DPIV image were to be centroided before the correlation of each interrogation region, the signal displacement would be enhanced relative to the background.

With Three Pulse DPIV, the combination of small accelerations over the longer laser pulse envelope and the stricter criterion for a correlation meant that centroided particle images would be less likely to lie in a straight line, with exactly the correct relative displacement. Thus, centroiding the image would drastically reduce the number of correlations for an interrogation region.

In practice, images often contained a relatively low number of complete particle image sets. Centroiding the image would mean that any correlation of a set of seeding particle images would count for one displacement. Due to the inevitable variations of local velocity in the interrogation region, these displacements might not overlap, so the signal in the correlation function corresponding to the true displacement would become smeared out. With only one correlation per particle image set, the height of such an extended signal peak could be indistinguishable from the noise.

For these two reasons, the final version of the PIV analysis routine did not centroid the PIV image.

4.4.8.2 Centroiding the correlation function.

Without centroiding the DPIV image, seed particle images in a triplet might extend over 3-4 pixels, enhancing the chance of a triple-correlation. As a result, the correlation signals could vary around the mean true displacement by a few pixels, i.e. there would be extended peaks in the correlation function, with signal levels closer to the levels of noise peaks. When a noise correlation occurred, i.e. images from different seed particles lying in a straight line with the correct relative spacing, the correlation would also be spread over more than one pixel in the correlation function. If the data in the interrogation region were of a high standard, the signal peak would still be the highest in the triple-correlation function, so it would be extracted as the first choice displacement.

With non-ideal data, it would be necessary to construct the analysis algorithm so that it could still extract the correct velocity vector. If the highest of the displacement peaks around the extended signal peak were not significantly higher than the noise level, the list of **npeak** highest peaks extracted from the correlation function (see 4.4.7) might be filled with noise peaks, with four or five entries to the list from displacements around each extended noise peak.

In such a case, when the true displacement peak was not included in the list of **npeak** highest peaks, the post-processing routine would be unable to supply the correct velocity vector for the region. The list of peaks held in memory could be enlarged, but peaks lower down the list would always have lower priority, e.g. there would be a small chance that the correct vector would be chosen if it occupied 20th position.

Ideally, the software would recognise extended peaks, and count each one only once when extracting candidates for the velocity vector. The solution implemented to achieve this was to perform a "highest peak centroid" function on the correlation function, which converted all the extended peaks to single pixel peaks, causing the signal peak to be much higher in the list of candidate displacements. The post-processing routine (see 4.4.9) was then more likely to select the correct displacement during the check for continuity with the neighbouring velocity vectors.

4.4.9 Continuity check.

Once the "first pass" velocity vector map had been produced, a post-correlation routine compared each vector with its neighbours. The user-defined criteria for continuity between neighbouring velocity vectors were the relative magnitude of the velocities and the relative angle. The continuity was considered bad if the ratio of *speeds* exceeded parameter **max_relspeed**, typically set to 3.0, or if the angle between the directions of the velocity vectors exceeded **max_angle**, typically 45-70°, depending on the degree of variation expected.

If a velocity vector had "good" continuity with more than half of its neighbours, it was considered to be a good vector. If it were a "bad" vector, each of the other **npeak** displacements extracted from the corresponding correlation function were checked for continuity with the neighbouring velocity vectors. The vector that had the highest signal in the correlation function and that had good continuity with the neighbouring vectors was chosen as the best fit. If none of the **npeak** displacements extracted were good, the region was noted as having no good velocity vector.

As vectors were altered to obtain better continuity between neighbouring regions, earlier comparisons were affected. The routine iteratively compared neighbouring vectors for the whole image until the best overall fit was obtained. This process actually took less than one second to compute. The new vector map was written to a file with the suffix ".pst", i.e. post-correlated vector map.

4.4.10 Interpolation.

If a local velocity vector could not be produced for an interrogation region, it could be left blank in the velocity vector map. If such a blank region were surrounded by vectors that had very similar velocities, both in magnitude and direction, it would be possible to assume continuity of flow and produce a vector for the blank region by interpolating from the neighbouring vectors.

The velocity vector map with the best continuity, "filename.pst", marked with a zero vector those regions where there was either insufficient seeding density or no non-noise peaks in the correlation function. Regions where there were signal peaks, but none had good continuity with more than half the neighbouring regions were marked in an array for possible interpolation.

The interpolation routine checked whether more than half of the neighbouring vectors had good continuity with each other. If this was the case, an interpolated vector was produced as the mean vector of those neighbouring vectors that had good continuity. The vector map produced after the interpolation was written to a file with the suffix ".int".

4.4.11 Other analysis method variations.

Some other analysis procedures are described below, which were explored briefly, but not incorporated into the final analysis software.

4.4.11.1 Summing vector maps.

Each velocity vector map of an individual DPIV image will give a picture of the instantaneous two-dimensional velocity field. If a set of velocity vector maps were summed, a mean velocity vector map would be produced. This is the correct method for producing such a mean map, i.e. it is essential to average after the vector is extracted from the correlation function.

Such images would be useful for

- providing important mean information about a flow.
- minimising the effect of erroneous velocity vectors.

This procedure clearly removes the instantaneous view of the flow-field structure, which is an important asset of PIV.

4.4.11.2 Summing images.

If individual DPIV images were electronically added, overlaid, or merged, the effect would be to produce an image with a much higher effective seeding density. This might be useful if it were difficult to achieve a satisfactory experimental seeding density. However, if the flow were not regular, each area of the mean image would contain particle image sets responding to different velocities, making it impossible to extract a single signal displacement from a correlation function.

If the seeding density were too low, more appropriate measures would be to :

- open the camera aperture to allow light from smaller particles to be detected,
- increase the laser power to increase light scattered from smaller particles,
- widen the laser sheet to include more seed particles,
- redesign the apparatus to allow more seed particles into the flow.

4.4.11.3 Summing correlation functions.

Under some circumstances, a set of DPIV images of some laminar flow could produce correlation functions where the signal to noise ratio were not as high as would be desired. It would be possible to sum corresponding correlation functions from different images. This procedure would assume that the signal peaks for the corresponding interrogation regions would overlap, and be enhanced, while the randomly distributed noise correlations would not overlap very often. However, even for a steady flow, signal peaks would not always overlap to the nearest pixel, so the overall signal peak would extend over many pixels.

4.4.11.4 Reapplying displacement to image.

Once the most likely displacement has been extracted from a correlation function for a particular interrogation region, one could attempt to apply the displacement to each particle image in the region, to see if there were a particle image pair or triplet corresponding to that displacement. When there was a close match, the images in the set could be linked, directly giving the velocity for that seed particle.

If this could be successfully applied throughout an image, the spatial resolution and confidence of the vectors would be very greatly enhanced. Essentially the technique would be using the correlation as a starting point for attempting a Particle Tracking analysis of a densely seeded image. This technique has been used by some groups, for example Goss et. al. (1991), Smallwood (1992), Driscoll et. al. (1994).

4.4.11.5 Manual post analysis program.

The PIV analysis software was developed with the aim of being able to extract the maximum number of good velocity vectors from an image, with the greatest amount of automation, whilst giving the user a large degree of flexibility in choosing and optimising the analysis parameters.

In practice, not every vector in the final vector map will correspond to the velocity of the flow for that region; some will be totally wrong. A further analysis procedure could be written to allow the user to manually inspect the image and choose which vectors were not acceptable. The user would be able to replace the vector with a zero vector, one from the list of displacement candidates (see 4.4.7), or an interpolated vector.

4.5 Summary.

When attempting to use DPIV in flows with significant flow direction variations, it was necessary to address the issue of directional resolution. A novel variation was investigated, in which a third, unequally spaced laser pulse of the same wavelength was added to the pulse envelope. The use of a triple-correlation allowed the local sign-resolved velocity for an interrogation region to be extracted directly from the correlation function. The occurrence of noise peaks was greatly reduced by the stricter criteria of the triple-correlation. However, the technique reduced the velocity bandwidth and it could not resolve zero velocities.

Experimentally, Three Pulse DPIV was less complex than other variations that resolve the flow direction. The only modification required to the two pulse DPIV system was the introduction of the beam from a second Nd:YAG laser, to produce the third laser pulse.

A large amount of effort was invested in writing an analysis package, with the emphasis on maximum speed and user flexibility, with minimum requirement for manual intervention. These were features that would be vital in a commercial package.

Several datasets of Three Pulse DPIV images were taken and analysed with the software. These illustrated the ability of the method to resolve the flow direction in

extreme cases of flow reversal, a large improvement over the conventional monochromatic two-pulse technique.

There are several areas where the technique could be developed further :

- An investigation into the use of a Fourier Transform algorithm with continuously variable region size, compared with the direct numerical correlation of particle positions.
- Alteration of the software to provide velocity measurements to sub-pixel accuracy.
- More rigorous testing of the system over a wide range of flows. This should allow optimum parameter values to be deduced with greater confidence so that the analysis could be further automated.
- Use of the technique in a turbulent combusting flow, where there would be large variations of velocity and density.

Chapter 5.

Premixed turbulent combustion and the use of laser diagnostics.

5.1 Introduction.

Premixed turbulent combustion has received much attention (Bray, 1990; Bradley, 1992). Accurate knowledge of the effect of turbulence on premixed flames will be important for the improved design of combustion devices, as well as for safety issues and models of turbulent combustion will inevitably require experimental data for validation. This chapter outlines some important aspects of turbulent premixed combustion theory, in particular the effects of curvature and strain on the burning rate of laminar flamelets in the high Damköhler number regime.

Instantaneous two-dimensional measurements of important combustion species permit the investigation of large scale structures in turbulent combustion. The hydroxyl (OH) radical is an important minor species in premixed combustion. It has an important influence on the principal reactions such that super-equilibrium levels in the reaction zone can be used to estimate the reaction rate. OH is a good flame-front marker which persists into the burnt gas region, allowing the unambiguous determination of flame-front contours and the application of fractal analysis to investigate the flame-front geometry and estimate the turbulent reaction rate.

This chapter describes the behaviour of the OH radical in more detail and the various potential methods for making experimental measurements of the concentration of OH in turbulent premixed flames. The most appropriate technique, Planar Laser Induced Fluorescence (PLIF), is described in detail. The implementation of OH-PLIF is covered, including optimisation of the image quality and minimisation of sources of error. This discussion leads into Chapter 6, which describes the experimental measurement of OH-PLIF in a rapidly expanding premixed methane-air flame at atmospheric pressure.

5.2 Premixed turbulent flames.

Flame theory has been described in detail by Clavin (1985), Kuo (1986) and Griffiths and Barnard (1995). A premixed flame will propagate through a stationary gas at a characteristic velocity. A non-wrinkled laminar flame will propagate normal to its flat flame-front at the *laminar burning velocity* u_L . It will have an adiabatic flame temperature T_{ad} and a laminar flame thickness δ_l . For methane-air stoichiometric mixtures, the burning velocity is 0.45 m/s and the flame temperature is 2222 K.

In the laminar flamelet model, the local mass burning rate of a flamelet is given by :

$$\dot{m} = \langle A \rangle \omega = \langle A \rangle \rho_r \langle u_L \rangle \quad (5.1)$$

where $\langle A \rangle$ is the local mean flamelet area per unit volume, ω is the mean rate of conversion of reactants per unit flamelet area, ρ_r is the reactant density and $\langle u_L \rangle$ is the mean laminar flame speed averaged over the surface of the flamelet.

5.2.1 Flame structures.

Flame structures can be classified by the Borghi diagram shown in Fig. 5.1 (Borghi, 1988). The horizontal axis is the ratio of the integral length scale, L , to the laminar flame thickness, δ_l . L is the average size of turbulence eddies, where most of the kinetic energy exists. δ_l represents the depth of the reaction zone of the flame, in which most of the heat release occurs. The vertical axis is the ratio of the r.m.s. turbulent velocity, u' to the laminar burning velocity S_l .

The Borghi diagram is split into different regions, depending on the nature of the flame structure. The relationship between the chemical timescale t_{ch} and the turbulence timescale t_t is given by the turbulent Damköhler number Da_t :

$$t_{ch} = \frac{\delta_l}{S_l}, \quad t_t = \frac{L}{u'}, \quad Da_t = \frac{t_t}{t_{ch}} \quad (5.2)$$

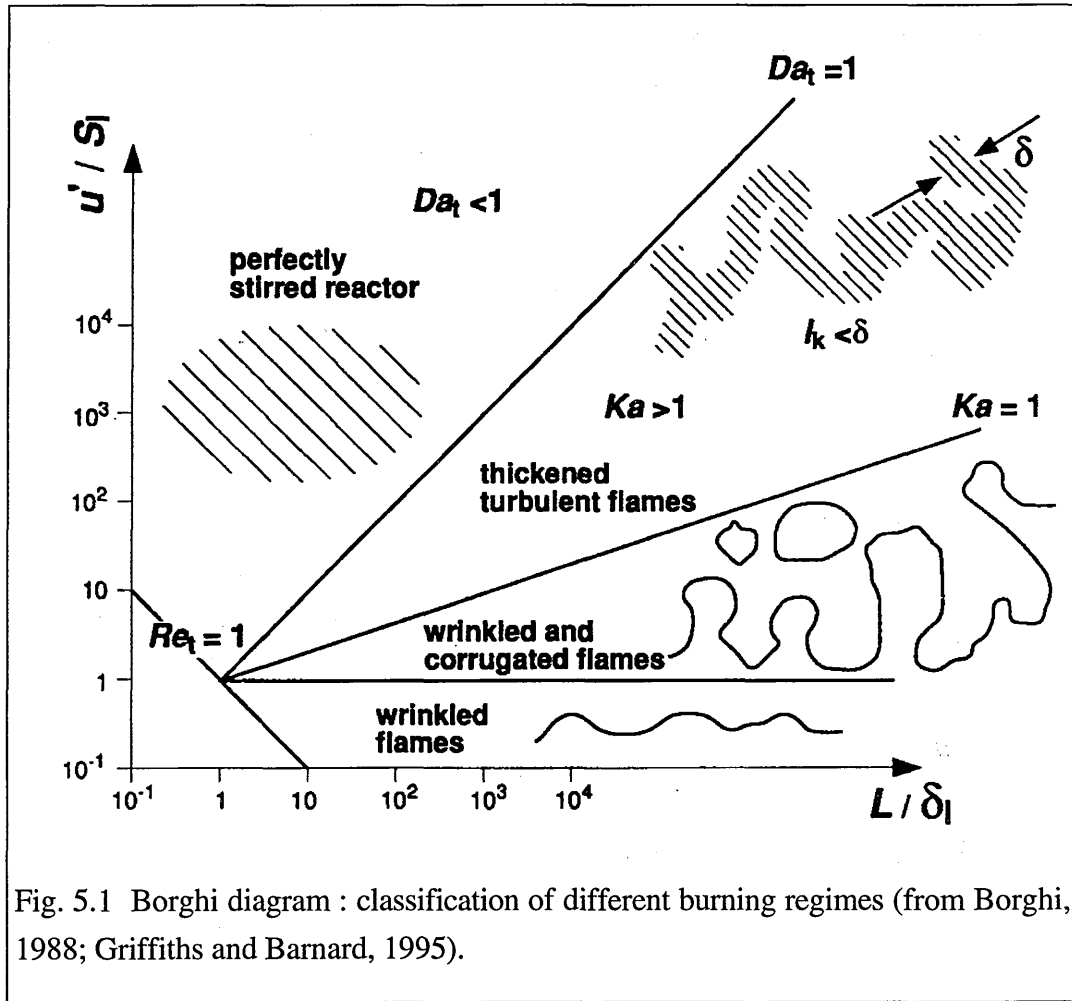


Fig. 5.1 Borghi diagram : classification of different burning regimes (from Borghi, 1988; Griffiths and Barnard, 1995).

The 45° line corresponding to $Da = 1$ broadly divides combustion into two regimes, depending on which timescale is shorter. This line does not extend to the origin, but is cut off at $Re_t = 1$, below which there are only laminar flames. Re_t is the turbulent Reynolds number, $Re_t = u'L/\nu$, where ν is the kinematic viscosity.

The lower right region of the Borghi diagram is a region where flame chemistry is fast compared with turbulence induced mixing of the gases. The laminar flamelet theory considers the turbulent flame in this region to consist of pockets of unburnt and fully burnt mixture, separated by small laminar flamelets which are stretched and distorted by the turbulence. It is applicable for $Re \gg Da \gg 1$ (Bray, 1990).

The upper and left area of the Borghi diagram, with $Da < 1$, refers to flames where the mixing rate is fast compared with the chemistry, resulting in a "perfectly stirred reactor". This region will not be considered further.

The other line on Fig. 5.1 refers to $Ka = 1$, where Ka is the Karlovitz flame stretch factor :

$$Ka = \frac{\delta_i u'}{S_i \lambda} \quad (5.3)$$

where λ is the Taylor microscale and u'/λ is the strain rate. Ka can be interpreted as the ratio of chemical to eddy lifetimes (Griffiths and Barnard, 1995).

5.2.2 Lewis number.

An important parameter in wrinkled flames is the Lewis number, Le . This was defined in Kuo (1986) as the ratio of energy transport to the rate of mass transport :

$$Le \equiv \frac{\lambda}{\rho C_p D} = \frac{a}{D} = \frac{\text{rate of energy transport}}{\text{rate of mass transport}} \quad (5.4)$$

where λ is the thermal conductivity, ρ is the density, C_p is the constant pressure specific heat, a is the thermal diffusivity and D is the binary diffusivity.

If $Le > 1$, thermal diffusion is preferred at the flame-front whilst if $Le < 1$, mass diffusion is preferred. It should be noted that Le is sometimes defined as the reciprocal of Eq. (5.4), for example in Griffiths and Barnard (1995).

The Lewis number is determined by the conditions and reactants at the flame-front. Table 5.1, adapted from Griffiths and Barnard (1995) shows Lewis numbers for different stoichiometries ϕ of methane-air mixtures, under conditions $T = 300$ K, $P = 0.1$ MPa. These figures were derived from a study by Tsuji and Yamaoka (1982) and one by Asato et. al. (1988). The calculations used the binary diffusion coefficients of the deficient reactants with nitrogen, because the concentration of nitrogen was very high compared with the concentrations of all other species. These figures are relevant to the experiment described in Chapter 6.

ϕ	a (cm ² /s)	D (cm ² /s)	Le
0.51	0.213	0.220	0.97
0.69	0.219	0.219	1.00
1.60	0.213	0.207	1.03

Table 5.1 Lewis number for different methane-air mixtures.

5.2.3 Wrinkled flames - curvature effects.

The wrinkling of premixed flames has been studied by Searby and Clavin (1986), Roberts et. al. (1992). Consider part of a wrinkled flame surface, shown in Fig. 5.2. There is a concave flame-front section and a convex section. If $Le > 1$, where heat flow from the flame to the unburnt reactants is more rapid than the influx of unburnt molecules, at the concave section the heat energy will be more focused on the reactants and the burning rate will be enhanced, compared with a flat flame-front. The opposite effect will occur for the

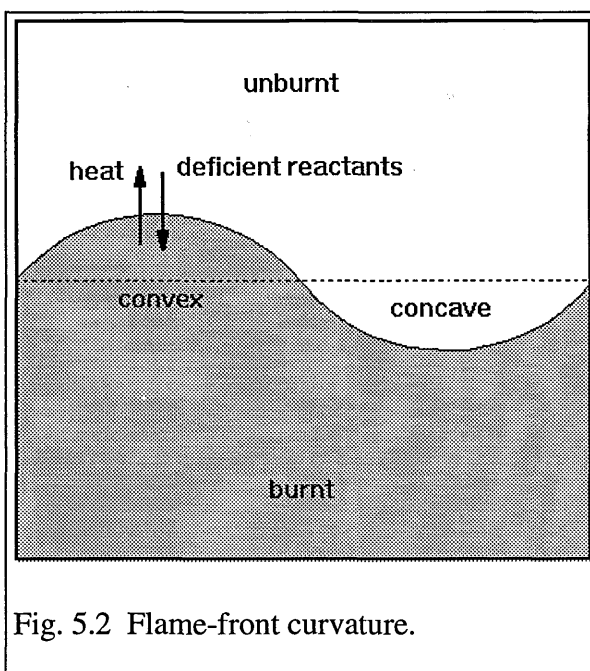


Fig. 5.2 Flame-front curvature.

convex section, i.e. the heat flow will be defocused and the burning rate will be suppressed. If $Le < 1$, with deficient reactant diffusion more important, the mass diffusion into the radical pool will be more focused at the convex section, resulting in a higher burning rate, whilst it will be defocused at the concave section, leading to a lowering of the flame temperature and burning rate. These variations in burning rate due to the local shape of the flame-front for $Le \neq 1$ are termed curvature effects.

5.2.4 Turbulent flames.

There have been many theoretical and experimental descriptions of the effect of strain on premixed turbulent flames, for example Williams (1985), Abdel-Gayed et. al. (1988), Law et. al. (1986), Law (1988). There are two principal and opposing influences of turbulence on the turbulent burning velocity (Bradley et. al., 1992b). The turbulent wrinkling of the flame-front will increase the flame area (Karlovitz et. al., 1953; Markstein, 1964). The Karlovitz flame stretch rate, K , is defined as the fractional rate of change of area, A , of an infinitesimal element of the surface :

$$K = \frac{1}{A} \frac{dA}{dt} \quad (5.5)$$

Since the burning rate is proportional to the flame area (Eq. 5.1), this would be expected to increase the turbulent burning velocity, u_t , and this is the case at low turbulence intensities.

At high turbulence intensities, the effect of turbulent straining of the laminar flamelets themselves becomes important. This acts to reduce the local laminar burning rate and can lead to quenching of flames at the quenching limit of strain rate (Cant and Bray, 1988).

Bradley et. al. (1992b) established a theoretical basis for correlating u_t/u_L in terms of the dimensionless group $KaLe$, including the effects of flame curvature and turbulence. Bradley (1992) collected curves of the variation of quenching strain rate with stoichiometry for a variety of hydrocarbon-air flame models and experiments. By converting the quenching strain rate s_q to the Karlovitz extinction stretch factor Ka_q and multiplying this by the Lewis number, it was tentatively proposed that the product Ka_qLe remained constant at flame quenching for different stoichiometries. The requirement for more experimental data in order to validate such theoretical models is clear.

5.2.5 Fractal analysis of turbulent flames.

Fractal analysis was applied to OH-PLIF images of turbulent premixed methane-air flames at atmospheric pressure in Chapter 6. The following section gives a background of the fractal theory and its application to turbulent flames.

5.2.5.1 Fractal nature of turbulent flames.

Section 5.2.1 described how in the wrinkled flame regime, it has been commonly assumed that the combustion within a turbulent flame is confined to asymptotically thin moving laminar flamelets which are embedded in the turbulent flow. The turbulent burning velocity can be approximated by the product of the flamelet surface area and the laminar burning velocity corrected for the effect of stretch and flame curvature (Gülder, 1990). Thus, the flamelet surface is an important property in turbulent combustion of this regime.

Instantaneous schlieren pictures (Abdel-Gayed et. al., 1988; Tsuji et. al., 1994) revealed the flamelet surface exhibiting self-similar wrinkling over a range of scales. Gouldin (1987) applied the fractal theory of Mandelbrot (1982) to the flamelet surface. The applicability and application of the fractal theory to turbulent flames has been described well by many workers, for example Gouldin et. al. (1988), Murayama and Takeno (1988), Mantzaras et. al. (1989), Gülder (1990) North and Santavicca (1990), Santavicca et. al. (1990), Shepherd et. al. (1990), Wu et. al. (1991), Bradley (1992), Kwon et. al. (1992), Shepherd and Ashurst (1992), Üngüt et. al. (1993a), Gülder and Smallwood (1995).

5.2.5.2 Fractal theory.

One method of measuring the area of a three dimensional surface would be to count the number of cubic boxes $N(\epsilon)$ of size ϵ required to cover the whole surface. The measured area would then be $N(\epsilon) \cdot \epsilon^2$. Such estimates of the area would increase with increasing resolution (decreasing ϵ) according to a power law (Mandelbrot, 1982). The variation of the area with ϵ for a fractal surface, on a log-log scale, exhibits a straight line with gradient $2-D$, where D is the fractal dimension of the surface, a measure of the surface roughness (Murayama and Taneko, 1988; Gülder, 1990). This is shown as the centre section of the graph in Fig. 5.3.

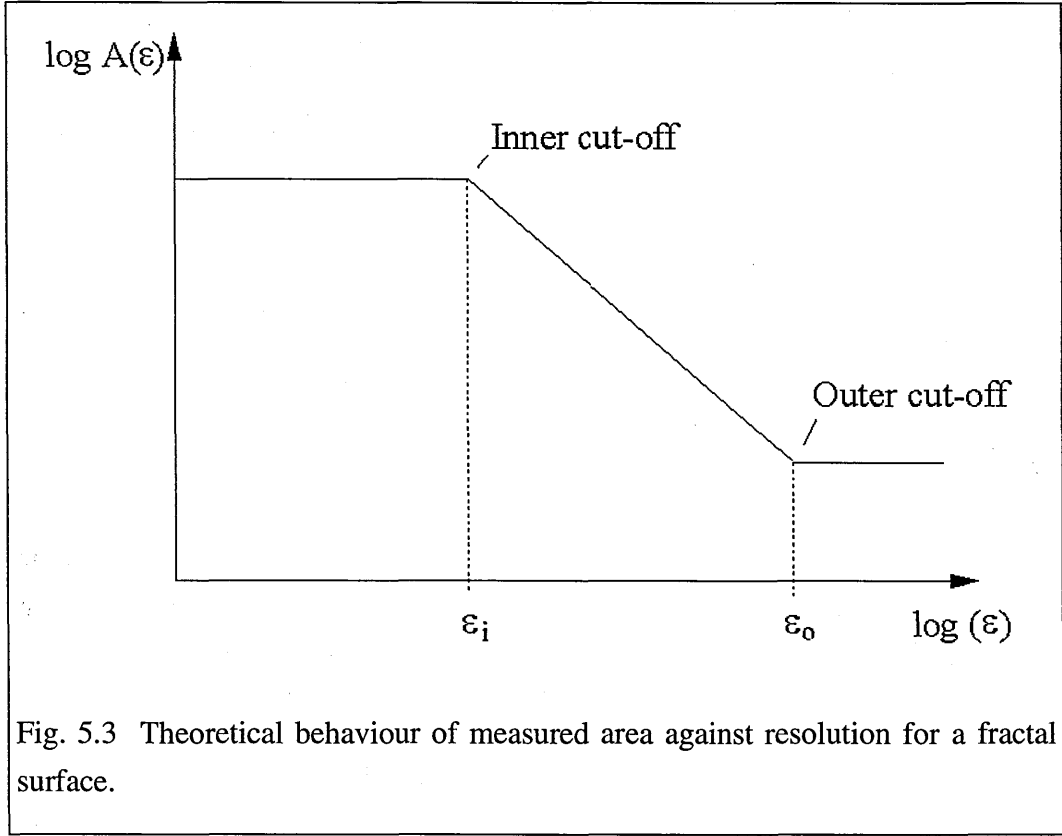


Fig. 5.3 Theoretical behaviour of measured area against resolution for a fractal surface.

Thus, the area $A(\epsilon)$ is given by :

$$A(\epsilon) \propto \epsilon^{2-D} \quad (5.6)$$

The range of scales over which this relationship holds will be bounded by cut-offs at both ends, imposed by physical limits. The inner cut-off ϵ_i is the minimum scale of wrinkling. Measuring the area with this resolution will give the true surface area of the flamelet. The outer cut-off ϵ_o is the maximum scale of wrinkling.

5.2.5.3 Fractal theory applied to turbulent flames.

Damköhler (1947) suggested that the ratio of the turbulent to laminar flame velocity should be proportional to the ratio of the instantaneous flame surface area of the turbulent flame, $A_t = A(\epsilon_i)$ to the flow cross section area, $A_o = A(\epsilon_o)$:

$$\frac{u_t}{u_L} \approx \frac{A_t}{A_o} = \left(\frac{\epsilon_o}{\epsilon_i} \right)^{D-2} \quad (5.7)$$

Thus, measurement of the three quantities ϵ_i , ϵ_o and D should allow the calculation of the turbulent burning velocity of a turbulent flame in the laminar flamelet region.

The intersection of a fractal surface with a plane, such as a two-dimensional PLIF image of a turbulent flame, will result in a fractal curve. The length of this curve could be measured in an analogous way to measuring the fractal area (Gouldin et. al., 1988). The total perimeter of the fractal curve would be measured with different step sizes, producing a relationship of the same form as Fig. 5.3. Fractal *curves* generated by intersections of a non-fractal plane with a fractal surface are characteristic of the fractal surface (Gouldin et. al., 1988), with fractal dimension D' given by $D = D' + 1$ where D is the fractal dimension of the *surface*. Thus, measuring ϵ_i , ϵ_o and D' for a flame-front in a PLIF image would allow a fractal analysis to be applied to the flame surface area, yielding the turbulent flame speed.

Gülder (1990) and Gülder and Smallwood (1995) have reviewed different values reported for the inner cut-off scale. Some accounts (Gouldin et. al., 1988) expected molecular diffusion to smooth the surface at small scales of wrinkling, implying that ϵ_i is determined by the Kolmogorov scale, η (the scale of smallest structures, through which most of the turbulence energy is dissipated). Peters (1986) suggested using the Gibson scale L_G . This is the scale at which an eddy would be consumed by a laminar flame, so eddies smaller than this cannot contribute to flame wrinkling and is larger than η . North and Santavicca (1990) proposed the larger of the laminar flame thickness and the Kolmogorov scale, while Murayama and Taneko (1988) measured the inner cut-off as the laminar flame thickness, though in their measurements, $\delta_l > \eta$.

In turbulent flows, it has been proposed (Peters, 1986; Gülder, 1990) that ϵ_o is comparable to the integral length scale. North and Santavicca (1990) measured outer

cut-off scales approximating to L , whereas the data of Muryama and Taneko (1988) and Gouldin et. al. (1988) showed outer cut-off scales larger than L .

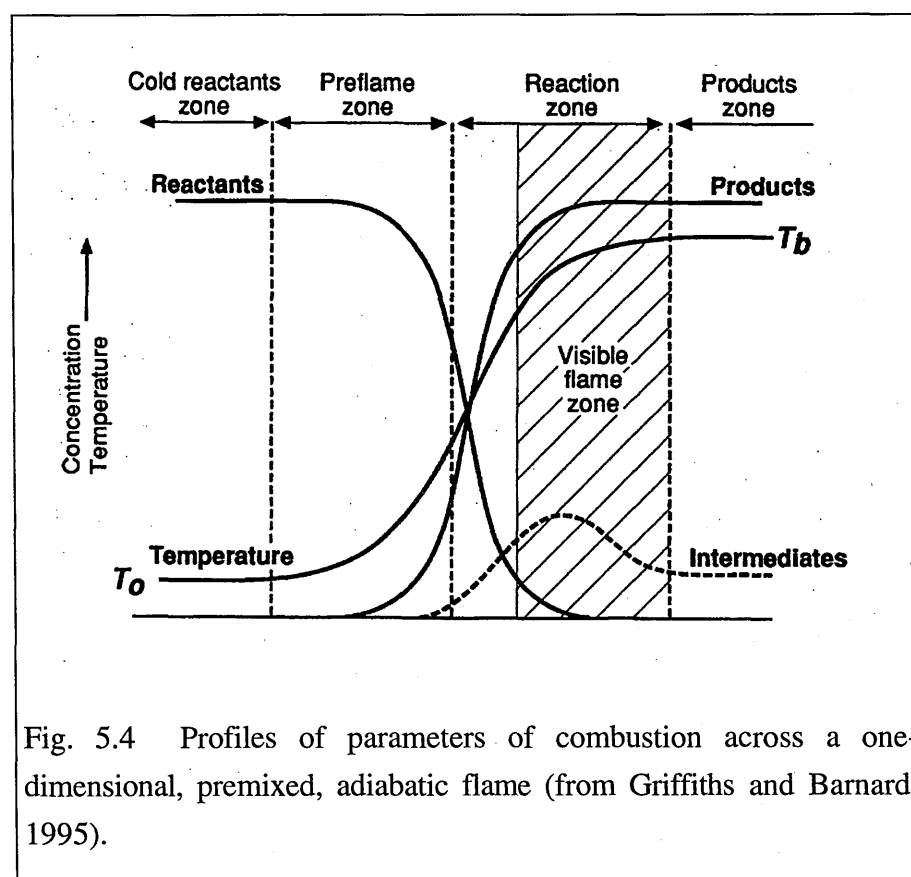
Fractal theory predicts a constant value for the fractal dimension D . Mandelbrot (1975) proposed a value 2.67, while Sreenivasan et. al. (1989) proposed the value 2.33. Reported measured values of the fractal dimension D vary between 2.12 (Mantzaras et. al., 1989) and 2.37 (Gouldin, 1987). Stretching of a flame will alter the fractal dimension from a theoretical constant value (Bradley, 1992).

The accurate measurement of the fractal parameters of turbulent flames should provide information on which processes cause wrinkling of different scales in turbulent flames and the effect of the wrinkling on turbulent flame speed.

5.2.6 OH radical.

The OH radical is very useful in understanding the behaviour of premixed flames, since it is both a flame-front marker and an indicator of local reaction rate.

The different regions of a flame were described by Westbrook and Dryer (1984) and Griffiths and Barnard (1995) and are shown in Fig. 5.4.



The typical OH concentration profile is shown as a dotted line. In unburnt regions the level of OH concentration is essentially zero. In the burning region there is a large concentration of OH as the radical pool sustains the combustion. In the burnt region, the combustion products consist principally of CO₂ and H₂O. The water vapour is subject to reversible dissociation: $\text{H}_2\text{O} \leftrightarrow \text{H} + \text{OH}$, with the equilibrium determined by the water concentration and the temperature. Thus, rather than falling to zero in the burnt region in the same way that CH does, the OH concentration decays to an **equilibrium** level. This shows unambiguously where the burnt and unburnt regions are, making OH a very good flame-front marker, allowing fractal analysis of the flame-front geometry.

The higher concentrations of OH in the flame are termed **super-equilibrium** OH. These concentrations are due to the combustion reactions in the reaction zone, where OH is an important intermediate. Thus, the amount of super-equilibrium OH is a measure of the reaction rate, or mass burning rate (Becker et. al., 1990; Farrugia et. al., 1994). Measurement of the OH concentration should allow the correlation of the variation of reaction rate with local flame curvature (see 6.5.3). If the velocity field were also measured, the burning rate could be correlated with turbulent strain on the flame.

5.3 Species concentration measurement techniques.

This section describes various methods for measuring species concentration, in particular the OH radical in a combustion environment. It concentrates on the most useful, Planar Laser Induced Fluorescence.

5.3.1 Physical Probes.

Traditional methods of measuring combustion phenomena involve the use of a physical probe inserted into the combustion environment. Temperature measurements can be made with thermocouples. Species concentration can be measured by using a cooled quartz probe to sample a region of the combustion, then using gas

chromotography or mass spectroscopy to give the breakdown of the various components in the mixture.

Such methods have been used commonly for many years, though there are a number of reasons why their accuracy is limited.

5.3.1.1 Perturbation.

Combustion processes are easily perturbed. The presence of a probe can alter the process it is trying to measure, either catalytically or through flow disturbance. For example, a probe can act as an additional source of turbulence in a flow-field. Practical devices often have specifically designed geometries so it would be desirable not to introduce new objects. Metal probes can cause combustion quenching due to conduction and this would be important when attempting to measure the combustion rate.

5.3.1.2 Resolution.

Due to its finite size, a physical probe will have a limited spatial resolution, typically of order 1 mm. To make measurements at more than one position, either an array of probes would be required, or one probe would have to be traversed over a grid. In both cases, there would be a significant separation between measurement locations compared with typical combustion length scales of order 10^{-3} m.

The temporal resolution of a measurement is controlled by the period of time over which the measurement is made. In the case of gas sampling, this can be of order 10 minutes, so the measurement can only produce a mean value.

5.3.1.3 Survivability.

Combustion environments, with elevated temperatures and pressures, can be extremely harsh. Physical probes can often be damaged over a period of time. As they are made more robust, they typically become physically larger, increasing the likelihood of perturbation of the application.

5.3.1.4 Relevance of measurement.

Physical probes do not perform measurements in-situ and need to be corrected, introducing ambiguity and inaccuracy. A thermocouple measurement must be corrected for radiation and conduction. Gas sampling probes measure chemical composition far from the sampling location, allowing chemical transformation in the lines to occur.

5.3.2 Laser Diagnostics.

Laser optical techniques avoid the problems of physical probes due to their non-intrusive nature. The laser light almost never perturbs the application, and measurements can be made in the most harsh of environments. The signal is obtained from a known measurement location and is thus usually unambiguous. Temperatures and species concentrations can be measured directly; corrections for competing processes are generally at a lower order of magnitude than for physical probes. Measurements can be made with simultaneously high spatial ($\sim 100\ \mu\text{m}$) and temporal (10 ns) resolution. Such techniques are not limited to equilibrium situations, so are ideal for measuring non-equilibrium phenomena.

The major disadvantage of laser diagnostics is the requirement of optical access, both for the introduction of the laser light and the detection of the signal. Devices often need to be custom designed with windows in appropriate positions, which may introduce limits on the conditions that can be achieved, such as maximum pressure and geometry. Maintaining clean windows can be a major design exercise. The application may be optically dense, making signal extraction difficult. The accurate collection of data requires a high level of operator expertise. Current techniques can not make comprehensive measurements of temperature and all species simultaneously.

Laser diagnostics can provide data which cannot otherwise be obtained, and can provide more accurate measurements of existing measurable quantities. The use of such techniques are likely to become more important as researchers attempt to understand combustion processes in more detail, particularly in view of the move towards attempting to use models to cut the cost and time of the design process of practical devices.

Good reviews of different laser diagnostics are given by Hanson (1986), Eckbreth (1988) and Taylor (1993).

5.3.3 Qualitative techniques.

Two techniques that provide qualitative combustion and flow images are shadowgraph and schlieren photography. Both can be realised with either conventional light sources or laser sources. The principle is that density variations in an application cause variations in refractive index. Hence, light rays passing through different density regions will be deflected differently, altering the brightness of the image. Both techniques provide line-of-sight mean images.

5.3.3.1 Shadowgraph photography.

Light diverging from a point source is transmitted as a parallel cylinder through a test field, via a lens. The transmitted light is imaged with a camera onto photographic film. Due to variations in flow density, light is deflected from its original path, causing regions of non-uniform illumination in the image. Shadowgraphs are sensitive to changes in the second derivative of the density (Merzkirch, 1987), so do not provide useful quantitative information. They are useful for imaging shock waves (Sajben and Crites, 1979), and can therefore show flame-fronts.

5.3.3.2 Schlieren photography.

This method is similar to shadowgraph, except that the transmitted light is focused to a point with a second lens, called the schlieren head (Merzkirch, 1987). Beyond this point, a camera images the test section onto film. A knife edge is placed at the intermediate focus. As light rays are deflected by variations in density, they will fall away from this focus point, and some will be blocked by the knife edge. Thus, the corresponding position in the image will be darker, indicating the density difference.

Large temperature gradients produce density differences that can be imaged with schlieren photography. One useful application is the visualisation of flame-fronts (Gatowski 1984, Gatowski 1985) which can reveal their fractal nature (Abdel-Gayed et. al., 1988; Tsuji et. al., 1994)

5.3.4 Inelastic scattering processes.

Inelastic scattering processes (Eckbreth, 1988; Greenhalgh, 1994) are those where the interaction between light and a molecule results in a transfer of energy. Some scatter processes are illustrated in Fig. 5.5. The scattered light can have a different wavelength than that of the incident light. For a given scattering cross-section of light and molecule, the total scatter will be proportional to the number of molecules, among other variables. Hence, inelastic techniques can be used to measure species concentrations.

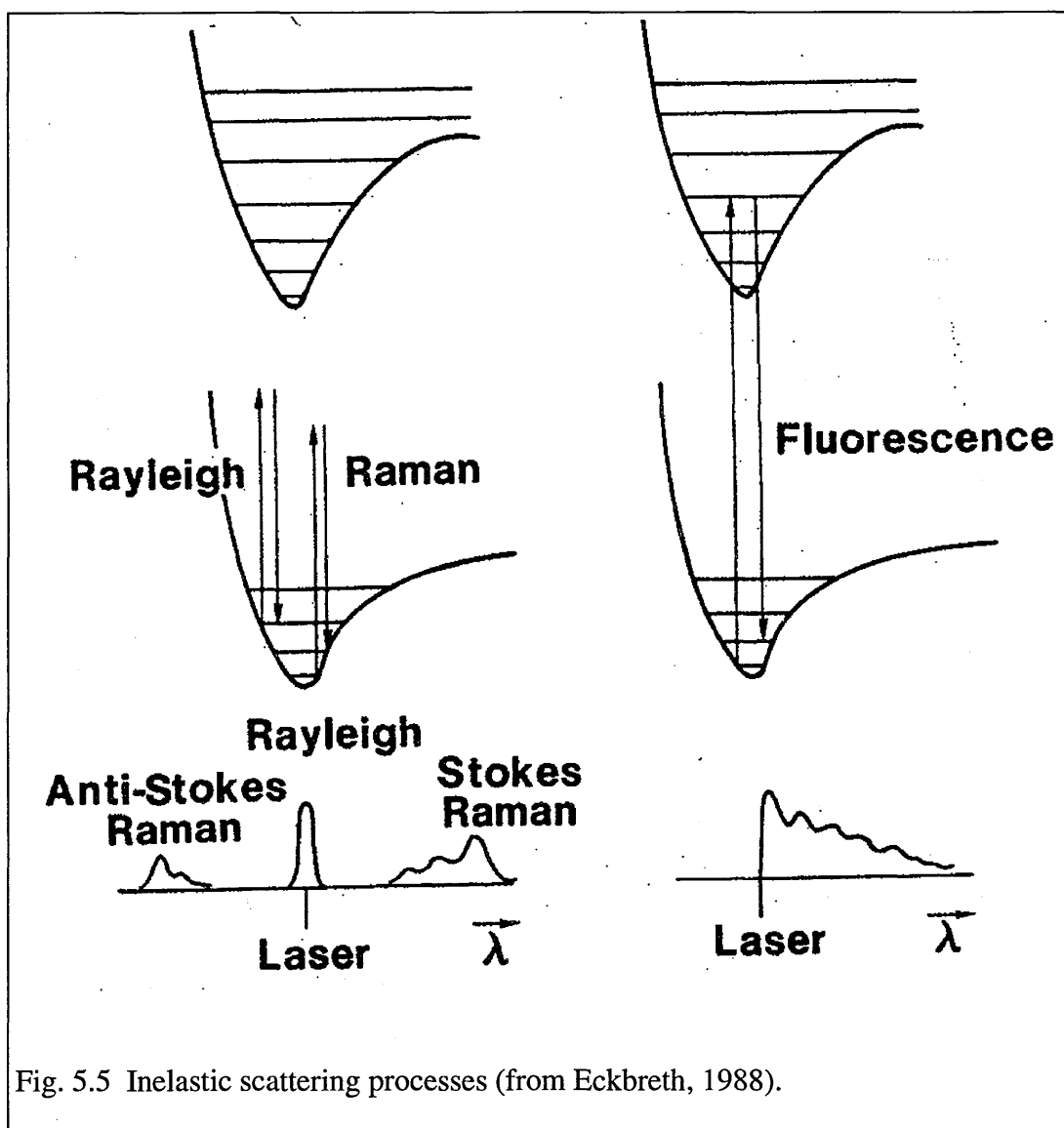


Fig. 5.5 Inelastic scattering processes (from Eckbreth, 1988).

5.3.4.1 Raman Scattering.

Raman scattering is a term used for general inelastic scattering of light from molecules, and is termed rotational, vibrational or electronic, depending on the nature

of the energy transfer which occurs. When performing measurements, a laser is used as an intense, coherent source of well-defined frequency.

Radiation scattered with a lower frequency, i.e. energy transferred to the molecule, is termed Stokes Raman, whilst that scattered with a higher frequency is termed anti-Stokes. This only occurs at elevated temperatures, when there are significant molecules in excited energy levels to transfer energy to the photons. Due to the quantization of the molecular energy states, the Raman spectrum resides at fixed frequency separations from the incident laser line, and is characteristic of the molecule involved. Thus, the Raman scattered signal is species specific and linearly proportional to the species number density.

Raman scattering has been widely applied to clean flames (Lapp and Penney, 1974; Eckbreth 1981). One advantage over LIF is that Raman scattering is not susceptible to collisional quenching (see 5.4.1). The lifetime of 10^{-12} secs makes it effectively instantaneous. However, with cross-sections typically of order 10^{-31} cm²/sr, resulting in collection efficiencies of 10^{-14} in flames, the signal is very weak. Thus, it has been limited to single point measurements of major species or averaging over many laser shots. If the incident laser wavelength is tuned near an electronic resonance of the molecule being probed, the Raman cross-section can be enhanced by up to six orders of magnitude (Szymanski 1967) - "near-resonant Raman spectroscopy". However, this variation has been seldom used.

5.3.4.2 Laser Induced Fluorescence.

When incident laser light is tuned precisely to an electronic resonance in a molecule, a photon can be absorbed into the molecule, raising its energy to an excited state. One of the subsequent paths for de-excitation is the spontaneous emission of a photon, as the molecule returns to a lower energy level. This emitted light is fluorescence. The amount of Laser Induced Fluorescence (LIF) emitted from one point in the measurement region is proportional to the local number density of the species, as well as other factors such as laser power and collection efficiency. In practical LIF experiments, electronic transitions are utilised because they lie in the 200 to 600 nm range of wavelength, convenient for high power pulsed laser sources. The LIF signal is emitted through 4π steradian solid angle, with a fraction gathered with a light sensitive recording device.

De-exciting molecules may fall to a number of energy levels, emitting light of various wavelengths. The shortest wavelength emitted corresponds to the maximum energy change, i.e. to the molecular ground level. This light, which has the same wavelength as the stimulating laser light is termed **resonance fluorescence** and is much stronger than fluorescence signals at higher, non-resonant wavelengths. However, if resonance fluorescence is collected, it is necessary to eliminate competing signals from Mie scatter, Rayleigh scatter and stray laser scatter.

Planar Laser Induced Fluorescence (PLIF) uses a sheet of laser light to produce an instantaneous two-dimensional map of species concentration. A sheet is formed using a Galilean telescope and passed through the measurement volume. The laser pulse duration will be typically 5-20 ns, and the fluorescent lifetime varies from 10^{-10} to 10^{-5} seconds. Thus, the signal gathered, usually orthogonally to the sheet, will give an effectively instantaneous two-dimensional image of the species concentration. A typical experimental PLIF set-up is shown in Fig. 5.6.

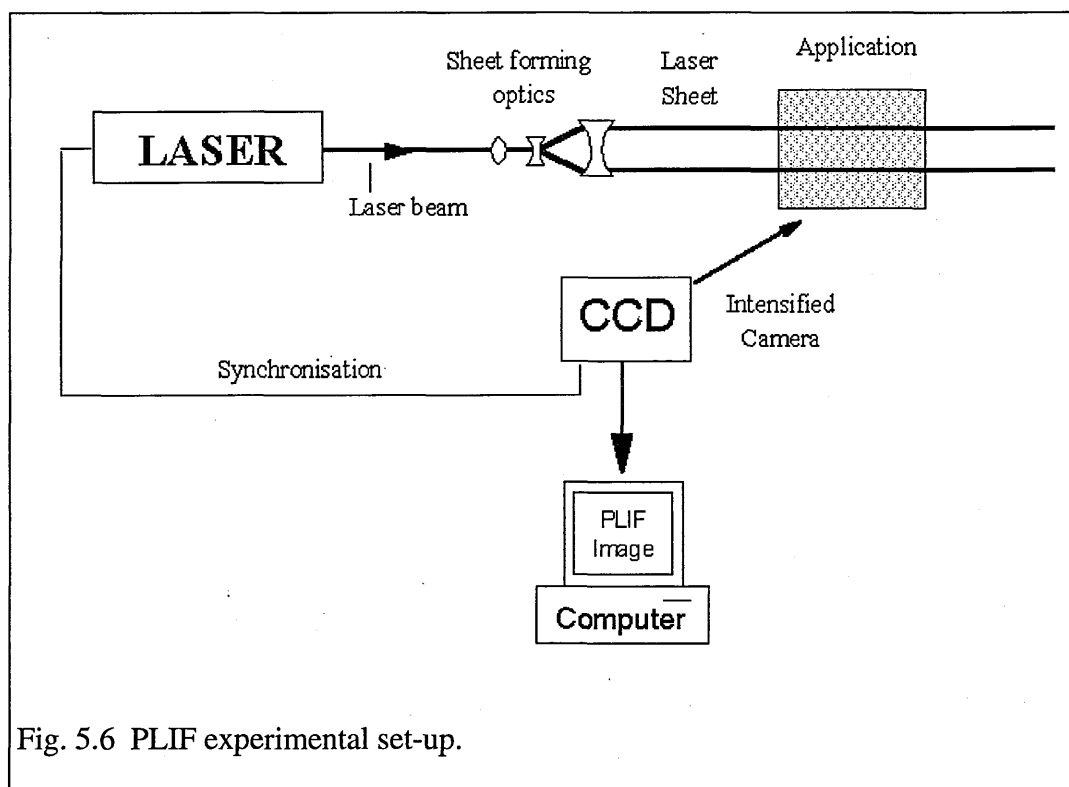


Fig. 5.6 PLIF experimental set-up.

LIF can also be used to measure temperature (e.g. Seitzman et. al., 1985), velocity (e.g. Hiller et. al., 1983) and pressure (e.g. Hiller et. al., 1986).

5.3.5 Elastic scattering processes.

During an elastic scattering process, there is no energy transfer between the incident light and the scattering molecules. Therefore, the scattered light will have the same wavelength as the incident light. Such elastic processes do not provide information about species number density, but they are often present when such measurements are made, and can contribute to signal noise.

5.3.5.1 Rayleigh Scattering.

Laser Rayleigh scattering is a well developed diagnostic tool, useful in both cold and hot reacting flows. The technique concerns scattering from particles with diameters small compared with the incident light wavelength ($d/\lambda \ll 1$), i.e. molecules in the vapour phase.

Rayleigh scattering has a cross-section, or signal strength, much larger than for Raman scattering, but smaller than for LIF. It can be used for measuring total gas concentration (Escoda and Long, 1983) or to infer temperature (Fourquette et. al., 1985).

5.3.5.2 Mie Scattering.

When the particle diameter is comparable with the wavelength, such that $d/\lambda \ll 1$ does not hold, the elastic scattering of light is termed Mie scattering. This holds for scatter from solid and liquid particles of size larger than about 0.1 μm . The signal is much stronger than from inelastic processes.

Mie scatter is generally used for flow visualisation, as described in detail in Chapter 2, or non-species specific concentration measurements (Stårner, 1983; Arnold et. al., 1992; Long et. al., 1993). If large particles are present when attempting to perform a LIF experiment, Mie scatter will dominate over the LIF signal.

5.3.6 Absorption.

Using a laser tuned to a molecular absorption line, a sensitive measurement of species concentration by absorption can be made (Eckbreth, 1988) using line-centre

techniques in the atmosphere (Byer, 1975) or in flames (Sulzman et. al., 1973). For axially-symmetric applications, geometric inversion can be applied to obtain spatial variations (McGregor, 1976), though this method is sensitive to inaccuracies.

5.3.7 Non-linear techniques.

There are several non-linear laser diagnostic techniques, which all exhibit very small cross-section, i.e. they produce very weak signal strengths. Coherent Anti-Stokes Raman Spectroscopy, CARS (Eesley, 1981; Harvey, 1981; Greenhalgh, 1988; Bradley et. al, 1992a) as a species concentration measurement technique is restricted to a limited range of major components in the combustion system such as N_2 , NO, H_2 , CO, O_2 , or H_2O . It has been used principally for pointwise temperature measurements and can produce data in highly luminous or sooting combustion environments. Degenerate Four Wave Mixing, DFWM uses laser beams of the same wavelength. This permits pointwise and two-dimensional concentration measurements to be made at very low signal levels (Ewart and O'Leary, 1986; Rakestraw et. al., 1990; Bush, 1995).

5.3.8 Summary.

Section 5.2.6 described how the measurement of the OH radical concentration can be useful in providing information about mass burning rates and flame-front geometry in premixed flames. Raman spectroscopy is capable of detecting species concentrations down to about 1000 ppm and is thus not able to provide information about radical species, such as OH, CH, NH, CN, which are present in concentrations of order 100 ppm in combustion applications. The best technique for obtaining such data is PLIF, which can detect such species down to sub-ppm levels to provide instantaneous two-dimensional concentration maps.

5.4 LIF Theory.

The basic theory of LIF is covered in several reviews, notably Eckbreth (1988), Seitzman and Hanson (1993), Greenhalgh (1994).

5.4.1 Molecular energy levels.

Generally, fluorescence denotes the radiation emitted by a molecule or atom when it decays by spontaneous emission of a photon in an optically allowed transition from a higher to a lower energy state (Banwell, 1972; Demtröder, 1982). The fluorescence occurs in parallel with other processes which act to de-excite the molecule, such as collisional energy transfer to other molecular states, and is proportional to the population of the upper state.

In a laser induced fluorescence measurement, the upper state is populated by a laser source with an emission frequency tuned to an optically allowed transition. The lower state is usually the ground state, since it is the only one with appreciable population, even at combustion temperatures.

After excitation, the molecules in the upper state can undergo a number of transitions, the most important being shown in Fig. 5.7. First, the molecule can be returned to its original state by laser induced stimulated emission. Absorption of an additional photon can excite the molecule to higher energy levels, including ionised levels. The internal energy of the system can be altered through inelastic collisions with other molecules. The energy level can be altered to different rotational, vibrational or electronic levels. The latter is referred to as "quenching"; the molecule returns to its ground state. Interactions between atoms in the molecule can cause pre-dissociation. The molecule can return to its lower level through spontaneous emission of light, possibly via nearby states - the LIF signal.

Considering a simple two energy level system like in Fig. 5.7, where A_{ul} is the Einstein coefficient for spontaneous emission, B_{lu} is the Einstein coefficient for stimulated excitation, B_{ul} for stimulated emission, I_ν is the laser spectral intensity. The total quenching factor Q_{ul} is a combination of the pre-dissociation quenching factor Q_{pre} and the collisional, or electronic, quenching factor Q_{elec} .

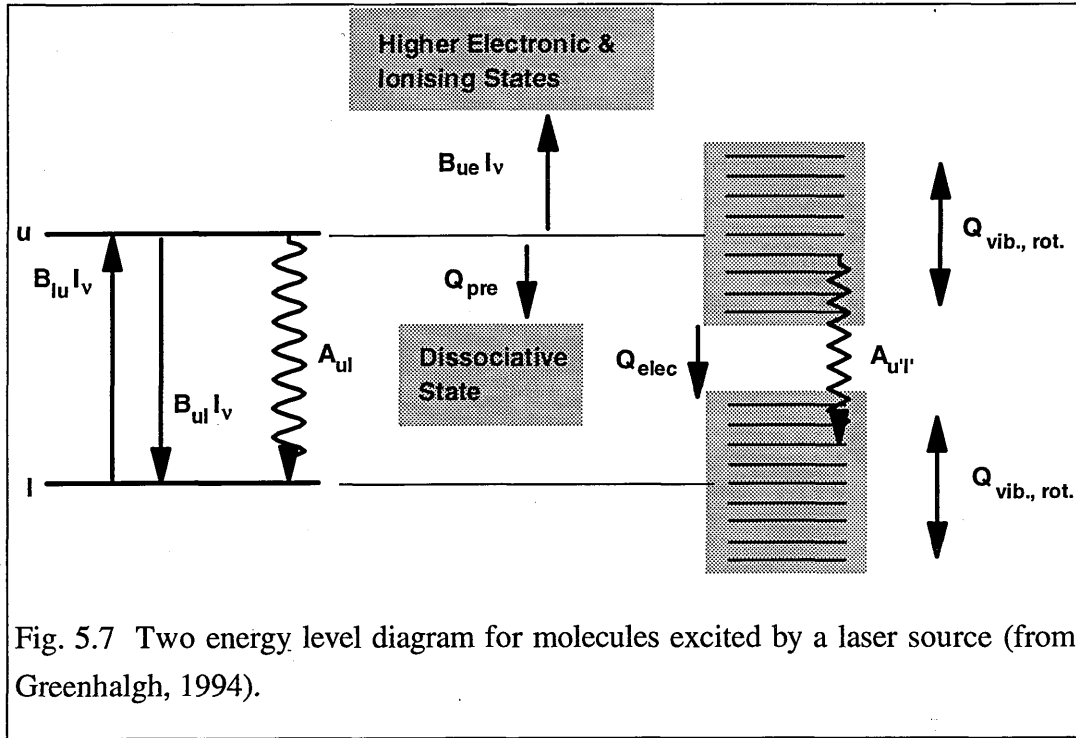


Fig. 5.7 Two energy level diagram for molecules excited by a laser source (from Greenhalgh, 1994).

The rate of change of upper level population is given by :

$$\frac{dN_u}{dt} = N_l B_{lu} I_v - N_u (B_{ul} I_v + A_{ul} + Q_{ul}) \quad (5.8)$$

with population conservation giving :

$$N_l + N_u = N_o \text{ (constant)} \quad (5.9)$$

The general expression for the population of the upper level is then :

$$N_u = \frac{N_o B_{lu} I_v}{(B_{lu} + B_{ul}) I_v + A_{ul} + Q_{ul}} \left(1 - \exp \left[- \left((B_{lu} + B_{ul}) I_v + A_{ul} + Q_{ul} \right) t \right] \right) \quad (5.10)$$

For relatively large t , the exponent falls to zero, giving steady state populations where :

$$\frac{dN_l}{dt} = \frac{dN_u}{dt} = 0 \quad (5.11)$$

The expression for the LIF signal, R , is given by :

$$R = N_u A_{ul} = \frac{N_0 B_{lu} A_{ul} I_v}{(A_{ul} + Q_{ul}) \left(1 + \frac{I_v}{I_v^{sat}} \right)} \quad (5.12)$$

where I_v^{sat} is defined as :

$$I_v^{sat} = \frac{Q_{ul} + A_{ul}}{B_{lu} + B_{ul}} \quad (5.13)$$

A comparison of the different excitation strategies for OH-PLIF measurements with respect to saturation has been given by Seitzman and Hanson (1992).

5.4.2 Linear regime.

At low laser excitation intensities, $I_v \ll I_v^{sat}$. In this case, Eq. (5.12) simplifies to:

$$R = N_0 B_{lu} I_v \frac{A_{ul}}{A_{ul} + Q_{ul}} \quad (5.14)$$

The fluorescence signal is proportional to the laser intensity, the "linear regime". PLIF images taken in the linear regime can be easily corrected for variations in the laser intensity by creating a calibration image from a uniform fluorescence source.

In the linear regime, the fluorescence signal is subject to variations in the collisional quenching term, Q_{ul} . To correct for collisional quenching generally involves knowing the partial pressures of all species present other than the one of interest, the rates for deactivation of the species of interest by all other species present, and the dependence of these rate constants on temperature. In certain applications (Becker et. al., 1990) the variation in Q_{ul} is relatively small, making the linear regime attractive for making LIF measurements.

5.4.3 Saturation regime.

If the laser intensity is increased, so that $I_v \gg I_v^{sat}$, the fluorescence equation becomes :

$$R = N_0 \frac{A_{ul}}{1 + B_{ul}/B_{lu}} \quad (5.15)$$

In this "saturation regime", the fluorescence is independent of both laser intensity and collisional quenching and the maximum fluorescence yield is obtained.

However, it can be difficult to achieve saturation in a PLIF experiment. Since neither the laser energy temporal or spatial profiles are top-hat, the sheet will not be saturated at the beginning and end of the laser pulse, nor at the edges of the image.

5.4.4 Pre-dissociative LIF.

If the excitation laser wavelength is sufficiently small, pre-dissociation of the molecules is possible, such that $Q_{\text{pre}} \gg Q_{\text{elec}}$. The rate of fluorescence in the linear regime then becomes :

$$R = N_0 B_{lu} I_v \frac{A_{ul}}{A_{ul} + Q_{\text{pre}}} \quad (5.16)$$

Changes in quenching due to local gas composition are eliminated and no specific laser spatial intensity is required. However, if $Q_{\text{pre}} \gg A_{ul}$, the high rate of pre-dissociative quenching of the excited energy state can cause the LIF signal to become very weak.

Pre-dissociative OH-PLIF images in spark ignition and diesel engines (Andresen et. al., 1988, Arnold et. al., 1992) have been achieved, using tuneable KrF excimer lasers at 248 nm, populating the $v = 3$ vibrational state of the $A^2\Sigma^+$ electronic system.

5.4.5 3D PLIF measurements.

Turbulent flames and flows require three-dimensional measurements to comprehensively investigate properties such as flame connectedness, surface to volume ratios, absolute mixing gradients and mixing topology (Patrie et. al., 1994).

2D images of combustion, such as OH-PLIF of premixed flames, often show islands of burning gases, such as described in Section 6.4.2. With no other information, it is difficult to determine whether such islands are actually separate from the main burning region or whether they are connected via an out of plane finger of flame. The 3D measurement of turbulent flame surface area allows fractal analysis to give the turbulent burning velocity (see Section 5.2.5). Mixing gradients in three dimensions are vital for accurate modelling of complicated combustion processes.

The general approach to 3D measurements of species concentration has been to collect an ensemble of 2D images from parallel sections through the application, at a sufficiently high rate that they can be considered to give simultaneous measurements. Yip et. al. (1988) used a resonant scanning mirror to move a laser sheet through a

turbulent premixed methane-air-biacetyl flame. An electronic framing camera took 12 fluorescence images at a rate of 10^5 images/sec such that the laser sheet moved one sheet thickness between frames. Patrie et. al. (1994) were able to record up to 20 PLIF images of an acetone seeded turbulent jet at a rate of 10^7 images/sec.

The quality of such rapidly taken PLIF images was not as high as single 2D images taken with cooled, slow-scan CCD cameras. Frank et. al. (1991) obtained higher quality images from four closely spaced parallel laser sheets of different wavelengths, imaging onto a single CCD camera. Signal discrimination was obtained with a multi-image optical component and the use of band-pass filters. Extrapolation of imaging hardware development suggests that rapid acquisition of high quality three-dimensional species concentration images should be possible in the future.

5.5 Experimental PLIF technique.

The general experimental set-up for making PLIF images is shown in Fig. 5.6. The basic elements are the laser source, sheet forming optics, application with optical access, image gathering camera system and the storage computer. Some issues that are important in obtaining useful images are described below.

5.5.1 Laser.

Lasers are used as an intense, coherent light source of well-defined wavelength to excite the molecules from which fluorescence is to be gathered. In choosing a laser for an experiment, there are three considerations.

- The laser must produce light of the same wavelength as an electronic excitation resonance from the electronic ground state.
- The laser pulse must be of sufficiently short duration for the image to effectively be an instantaneous "snapshot", unless fast exposure gating is performed, for example with an intensifier.
- There must be sufficient energy in each pulse to produce a detectable LIF signal.

These considerations usually point to the use of a pulsed laser or a dye laser pumped by a pulse laser. Often, a single wavelength laser will be suitable, e.g. an XeCl excimer laser, with output at 308 nm has been widely used for producing OH fluorescence ($X^2\Pi-A^2\Sigma^+$, 0-0 transition; $Q_1(3)$ line is at 308.154 nm). If this is not the case, a dye laser will be used to achieve the correct wavelength, though it will typically have a lower pulse energy.

5.5.1.1 Sheet forming.

The factors for calculating the laser sheet characteristics were covered in Section 2.4.5.5. The primary goals in obtaining PLIF images are to achieve the highest signals and best spatial resolutions, which both point to the formation of a thin sheet, typically $\sim 200\ \mu\text{m}$.

5.5.2 Camera.

Whilst PLIF images could be collected with a photographic camera, it has been common practice to use a CCD camera, such as described in Section 2.4.7. The array size will be less important in PLIF work than with DPIV, with arrays of size 600×400 pixels being adequate for many applications. The principal features of CCD cameras are low noise, linear response, instant viewing and electronic format.

5.5.3 Intensifier.

In many fluorescence experiments, particularly involving minor species such as OH, the signal will be too weak to give a useful signal when imaged directly with a CCD camera. The use of higher laser energy would not solve the problem, since the signal would become saturated. The solution is to use image intensifiers, described by Seitzman and Hanson (1993).

An intensifier front plate consists of a photocathode. LIF photons incident on the photocathode are converted to photoelectrons and are accelerated away to a thin micro-channel plate (MCP) by an applied voltage that can be controlled to a temporal resolution of order 10^{-9} s. The MCP contains many ($\sim 10^6$) small-diameter ($\sim 10\ \mu\text{m}$) channels. The photoelectrons undergo cascade amplification along the micro-channels

before striking the phosphor-coated back surface, creating new photons. Thus, the original image is reproduced, with the signal strength amplified.

Another function that can be performed by an intensifier is fast gating. If the laser pulse had a duration of 20 ns, the amplification voltage might be applied for 50 ns around the pulse. This would be considerably shorter than the minimum shutter duration of the CCD camera, which might be 5 ms. Thus, the detected image could be limited to the LIF signal, which might otherwise be swamped by non-laser light, e.g. flame luminosity, even spectrally filtered. Fast gating also allows c.w. lasers to be used without mechanical choppers or image smearing.

Intensifiers can perform a third function: wavelength conversion. The intensifier can convert the LIF signal, which is often in the blue or U.V. region to wavelengths in the centre of the visible spectrum, where CCD cameras are more sensitive.

The disadvantages of intensifiers are limited spatial resolution and limited linear dynamic range, due to charge saturation in a micro-channel. The back plate can be either lens-coupled or fibre-optically coupled to the CCD array. The use of fibre-optical coupling is preferable since it can provide a collection efficiency close to unity, rather than a more typical 25 % for lens coupling. In addition, it avoids the focusing errors of lens coupled systems and the difficulty in maintaining perfect alignment. However, fibre-optically coupled CCD-intensifier systems are more expensive.

5.5.4 Image resolution.

The spatial resolution of a PLIF image will have three contributing factors. The first will be the maximum possible resolution, determined by the physical space imaged by one pixel. This will typically be of order 100 μm when imaging 50 x 50 mm with a 500 x 500 pixel array of 25 x 25 μm pixels. However, the lens-intensifier optical system will have a lower spatial resolution of order 200-300 μm . This will determine the image resolution in the plane of the laser sheet, i.e. the accuracy with which a signal can be placed.

Normal to the plane of the laser sheet, the uncertainty in signal position is determined by the sheet thickness ($\sim 200 \mu\text{m}$), assuming it is lower than the depth of field ($\sim 4\text{-}5 \text{ mm}$) of the imaging lens. Whilst the sheet thickness did not contribute to the resolution of DPIV images (see 2.4.9.1), it must be included in assessing the spatial resolution of PLIF images.

These independent uncertainties can be combined in quadrature to give the overall three-dimensional spatial resolution of the PLIF images, typically $\sim 400\ \mu\text{m}$.

5.5.5 Synchronisation.

Accurate synchronisation can be used to collect light for the shortest possible time, in order to minimise noise from non-laser light sources such as flame luminosity. The laser pulse duration in all experiments was in the range 5-20 ns. Intensifier gates can accurately enable the light gathering for a well-defined time period, typically 50 ns, centred around the laser pulse. This allows the camera shutter to be left open for a longer period ($\sim 10\ \text{ms}$), since it will only gather significant signal when the intensifier voltage is applied.

When the laser can be fired on demand, e.g. XeCl excimer, with a steady application, the typical synchronisation pattern can be straightforward:

CAMERA READY $\rightarrow$ LASER SYNC. $\rightarrow$ INTENSIFIER SYNC.

When the PC controlling the CCD camera has finished writing an image to disk, it causes the camera shutter to open for approximately 20 ms. About 10 ms later, with the shutter fully open, a trigger signal will instruct the laser to fire one pulse. A trigger from the laser will be sent to the intensifier controller approximately $1\ \mu\text{s}$ before the pulse. A user-adjusted delay will be introduced, before the intensifier is switched on for approx. 60 ns. The image is collected and written to disk.

When using a Nd:YAG laser, for example to pump a dye laser, the timing will be subject to the flashlamp cycle (see 2.4.5.4). If the application is not stationary, the laser pulse and camera exposure must be synchronised with the correct position of the application. This was the case for the measurements in Chapter 6 and the synchronisation circuit required is described in Section 6.2.4.

5.5.6 Data transfer and storage.

Each PLIF image taken with a small sized (500 x 500 pixel) CCD camera involves transfer and storage of about 0.5 Mb of data. The transfer from the camera to the computer might take approximately 1-2 secs, with the writing to hard disk another 1-2 secs. Thus, images can be taken at a rate of one every 4-5 secs. This allows a large number of images to be taken in a relatively short period of time, making it easier to

keep the application "on condition" for the duration of a dataset. However, such a frame rate would not be high enough to give the time evolution of an the measured property.

A dataset of 100 such images involves approximately 50 Mb of data. In 1991, when this work commenced, this represented the size of a typical PC hard disk. By 1995, entry level hard disks were sized 1 Gb, so many datasets could be taken in quick succession. As data transfer, compression and mass storage devices continue to improve rapidly, the hardware will become less of a constraint in data acquisition. However, the analysis time is not likely to be significantly shortened, since it usually involves a lot of manual intervention.

5.5.7 Errors in PLIF images.

The sources of error in PLIF images have been described comprehensively by Seitzman and Hanson (1993). Errors can be systematic or random.

5.5.7.1 Systematic errors.

Systematic errors are the same for every image and are caused by dark current, background laser scatter, variation of pixel response and laser sheet profile and laser power absorption. Each of these sources of error are described in detail in Section 6.3. In principle, these errors can all be corrected using calibration measurements.

5.5.7.2 Random errors.

Random errors can be generated both in the application and in the detection system. In the application, radiation trapping is the absorption of fluorescence signal between the laser sheet and the detection system, for example by the excited species.

Noise is generated at each stage of the detection system; at the photocathode, photoelectric emission is Poisson distributed (Verdeyen, 1981), resulting in "shot noise" equal to the square root of the number of emitted electrons. The cascade gain process both amplifies the shot noise and introduces new noise. The CCD array detection process introduces noise due to detector shot noise (conversion of photons to charge), dark signal noise, offset noise (KTC) caused when a pixel is reset and

thermal noise produced by the random motion of charge carriers in resistive elements. Finally, assuming the detector is not saturated, the analogue to digital (A/D) conversion electronics introduce discretisation noise.

In general, each of these detection noise sources are independent, giving a total detection noise of :

$$\sigma_{\text{tot}} = \left[\left(\sigma_{\text{tube}}^2 + \sigma_{\text{det.shot}}^2 \right) + \left(\sigma_{\text{dark}}^2 + \sigma_{\text{KTC}}^2 + \sigma_{\text{thermal}}^2 + \sigma_{\text{A/D}}^2 \right) \right]^{1/2} \quad (5.17)$$

which is a combination of signal-dependent shot noise and signal independent camera noise. By using cooled, slow-scan CCD detectors, the camera noise can be minimised such that the total noise is dominated by shot noise. The shot noise and radiation trapping can be quantified, but not corrected, due to their random nature.

5.6 Application of PLIF: measurement of OH.

The bulk of fluorescence imaging has been concerned with species concentration measurements (Hanson, 1986). Examples of its use are numerous and diverse, with many examples given in Hanson (1986), Eckbreth (1988), Seitzman and Hanson (1993), Greenhalgh (1994).

5.6.1 Combustion applications.

The interest of this work was in studying flame-front effects, specifically in atmospheric premixed flames. There are different species that can be imaged in order to provide information in combustion applications. The CH radical marks the location of the thin, instantaneous reaction zone (Jeffries et. al., 1986; Allen et. al., 1986; Namazian et. al., 1988; Stårner et. al., 1992), while OH is also an indicator of flame-front and reaction rate (Kychakoff et. al., 1984a). The fuel can be imaged (Berckmüller

et. al., 1994), or various products such as CO (Haumann et. al., 1986) and NO₂ (Cattolica and Vosen, 1986).

5.6.2 OH-PLIF.

The measurement of OH concentrations with PLIF was first reported by Kychakoff et. al. (1982). There have been many examples in the literature of attempts to make such measurements fully quantitative, for example Garland and Crosley (1986), Kohse-Höinghaus et. al. (1988), Seitzman and Hanson (1992), Quagliaroli et. al. (1993), Seitzman and Hanson (1993).

OH-PLIF has been used to probe the properties of combustion systems by, for example Kychakoff et. al. (1984b), Jeffries et. al. (1986), Kohse-Höinghaus et. al. (1986), Seitzman et. al. (1990), Puri et. al. (1992), Stårner et. al. (1992), Orth et. al. (1994), Seitzman et. al. (1994), Namazian et. al. (1994).

Becker et. al. (1990) investigated flame extinction in turbulent combustion in a square piston engine. For lean mixtures, the flame temperature was lower, resulting in lower equilibrium values of OH, compared with stoichiometric mixtures. There were examples of discontinuities in the super-equilibrium OH zone, indicating flame quenching. The image analysis calculated the local ratio of the average maximum super-equilibrium OH signal $\langle S_{\max} \rangle$ to the equilibrium OH signal S_{eq} in order to give the local flame speed ratio :

$$\frac{\langle u_L \rangle}{u_L^0} = \frac{\langle S_{\max} \rangle [OH]_{\text{eq}}^0}{S_{\text{eq}} [OH]_{\text{max}}^0} \quad (5.18)$$

where $[OH]^0$ are the maximum and equilibrium OH concentrations calculated for unstrained laminar flames. The results showed that the lean burning velocity was lower than for stoichiometric mixtures and that the effects of flame curvature were important in this case, where the turbulence intensity was not sufficiently high for turbulent straining effects to be important.

5.7 Summary.

In turbulent premixed combustion, the effects of flame curvature and turbulent strain rate have received much attention. Measurement of the OH radical concentration allows unambiguous determination of the flame-front geometry, allowing fractal analysis of the wrinkling of the flame. The super-equilibrium levels of OH in the reaction zone are a measure of the local mass burning rate. Two dimensional instantaneous imaging of OH allows the correlation of local variations of burning rates with local flame curvature and strain rate.

Planar Laser Induced Fluorescence, using a pulsed laser and an intensified CCD camera, is an ideal technique for making such instantaneous two-dimensional measurements of OH concentration. An experiment applying OH-PLIF to a turbulent premixed methane-air flame at atmospheric pressure is described in Chapter 6.

Chapter 6.

Investigation of turbulent premixed flames using OH-PLIF.

6.1 Introduction.

In Chapter 5, OH-PLIF was described as a useful, well-established tool for making instantaneous two-dimensional measurements of flames. The OH radical concentration can be useful, since it is a good flame-front marker and can be used to calculate the local instantaneous reaction rate (Section 5.6.2).

In order to explore this technique, experimental images were obtained from rapidly expanding methane-air flames at atmospheric pressure. The particular apparatus, located at the sponsor's laboratories, provided excellent optical access for applying laser diagnostics to a simplified example of combustion, downstream of an obstacle array.

Several hundred OH-PLIF images were obtained from premixed methane-air flames and were corrected for systematic error sources. Under the influence of turbulence, these flames became wrinkled and distorted, introducing the effects of flame curvature and turbulent flame stretch. Visual inspection revealed several interesting features such as burning rate variations and flame quenching. Fractal analysis was applied to the flame-front contours to extract the inner cut-off values and the local reaction rate was correlated with the local class of curvature.

Such measurements can enhance fundamental knowledge of turbulent premixed combustion as well as allowing investigation of practical issues, such as the safety implications of the ignition of accidental vapour emissions, in environments where obstacles such as pipes could cause flame acceleration.

6.2 Experimental detail.

6.2.1 Application.

Highly turbulent premixed flames at atmospheric pressure were produced in a wind tunnel by spark-igniting a methane-air premixture of pre-determined stoichiometry. The travelling flame encountered a 54 % blocked grid, bursting through into a turbulent downstream region.

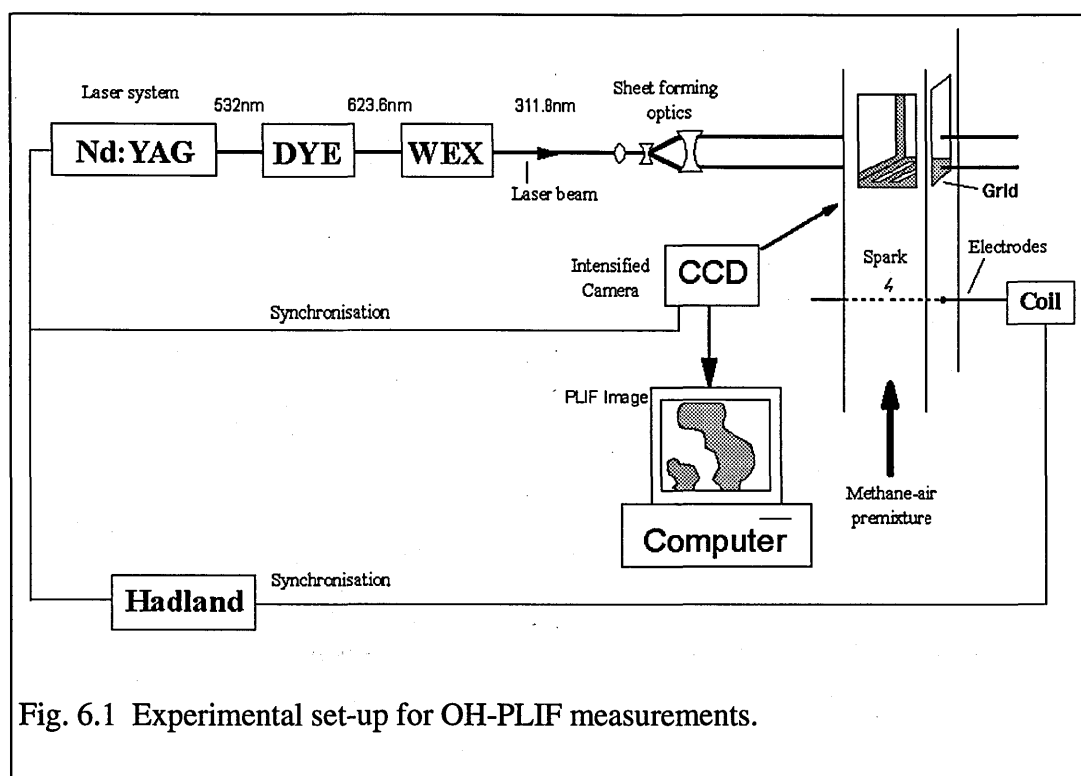


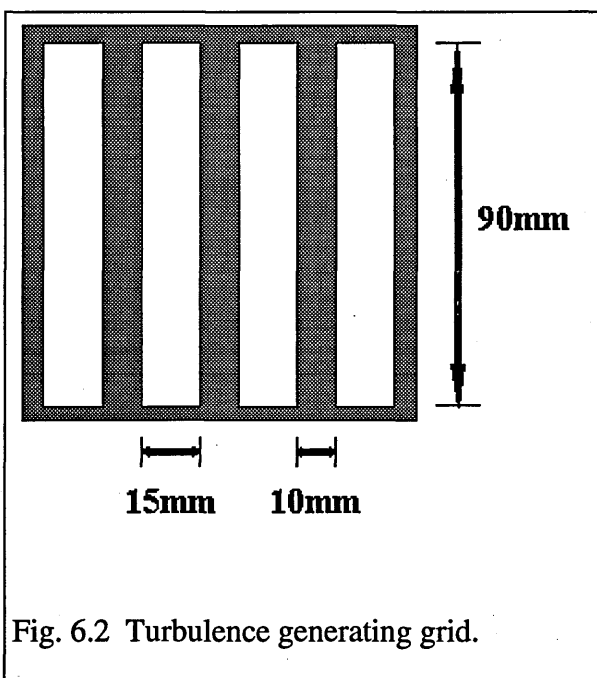
Fig. 6.1 Experimental set-up for OH-PLIF measurements.

The apparatus is shown in Fig. 6.1. A constant volumetric fan was used to establish the bulk gas flow of 21.4 l/min through the vertical wind tunnel (cross-section 100 x 100 mm), most of which was air from the laboratory. A metered amount of methane was introduced, to produce an ignitable methane-air mixture of well defined stoichiometry. This was allowed to mix through baffles along approximately 3 m of pipe, upstream of the measurement region.

After approximately 30 seconds of mixture preparation, the methane supply upstream was closed, followed immediately by ignition, using a standard motor coil connected to two electrodes. The laminar flame developed over 200 mm before encountering the turbulence generating grid, shown in Fig. 6.2. The grid was square, with side 100 mm and contained four slots of dimension 90 x 15 mm. It was orientated with the slots parallel to the axis of the camera, to produce an approximately two-

dimensional flame geometry in order to minimise out-of-sheet variations. Downstream of the grid, LDA characterisation of the flow-field reported by Üngüt et. al. (1993b) showed a peak mean velocity of 12.5 m/s, with a peak turbulent velocity of 3.5 m/s.

Immediately downstream of the obstruction, a laser sheet was directed through the flame and the Planar Laser Induced Fluorescence was collected orthogonally with an intensified CCD camera. One image was taken with each ignition, with a turnaround time of ten minutes.



6.2.2 Laser system.

The OH fluorescence was gathered on resonance at 311.8 nm. This wavelength pumps the $P_1(8)$ line of OH in the (0,0) band of the $A^2\Sigma^+ \leftarrow X^2\Pi$ system (Dieke and Crosswhite, 1962; Üngüt et. al. 1993a). This fluorescence line shows a very weak dependence on temperature (< 6% between 1300-2500 K : Morley, 1982), so the signal did not need correction for temperature variations.

To produce the excitation light at the wavelength 311.8 nm, a frequency-doubled Nd:YAG laser (Quanta-Ray DCR-3, wavelength : 532 nm, pulse duration ~ 8 ns, pulse energy : 350 mJ) was used to pump a red dye (DCM) in a tunable dye laser (Quanta-Ray PDL-2), tuned to 623.6 nm. The output was frequency doubled (Quanta-Ray WEX) to the excitation wavelength, which was in the near ultra-violet.

The beam was formed into a sheet using a 1 m focal length spherical lens and a combination of a -12 mm and a +100 mm focal length cylindrical lens, used as a Galilean telescope. This produced a laser sheet of height 75 mm and thickness at waist of 289 μm , measured with a 1D photodiode array.

The laser pulse energy of up to 10 mJ per pulse was sufficient for up to 4000 counts of resonant fluorescence signal in the linear regime (Seitzman and Hanson, 1992).

6.2.3 Camera system.

An intensified, water cooled, slow-scan 12-bit CCD camera (B+M) was connected to a frame grabber. The region of the camera chip used was an array of 576 x 341 pixels, each of dimension 23 x 23 μm . The fluorescence was imaged with a Nikkor UV f/4.5 lens of focal length 105 mm.

The camera imaged an area of size 75 x 50 mm in the plane of the laser sheet, giving the resolution of each pixel as 114.9 μm . This field of view included the centre two of the four gaps in the turbulence generating grid. Taking into account the intensifier-camera point spread function and the lens limitation, the resolution of the optical system was 300 μm , which was measured empirically by resolving multiple parallel fine lines in the focal plane. With the laser sheet thickness, the combined spatial resolution of the PLIF images was 420 μm .

Useful images were archived on an Atari AT computer. Each image occupied 392 kB of disk space, allowing up to 60 to be held on the 20 Mb hard disk. The limited space and lengthy transfer time of 90 seconds were a considerable constraint on the acquisition of data.

6.2.4 Synchronisation.

The usual synchronisation circuit for obtaining PLIF images, applicable to stationary applications, was described in Section 5.5.5. With the turbulent flames in the wind tunnel, it was necessary to synchronise the laser pulse and camera exposure with the arrival of the flame in the imaged region.

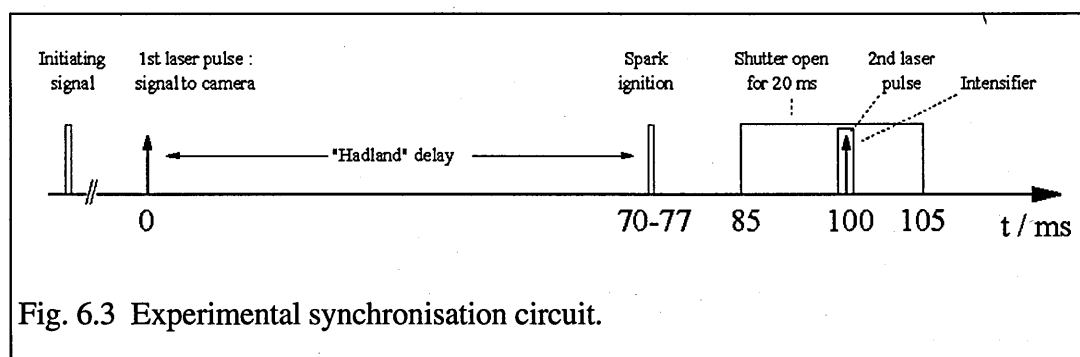


Fig. 6.3 Experimental synchronisation circuit.

The triggering of the system was dependent on the Nd:YAG laser repetition rate of 10 Hz (see 2.4.5.4) and is illustrated in Fig. 6.3. Once the system was armed, the next flashlamp signal from the Nd:YAG laser initiated the sequence. The camera-intensifier system was synchronised with the second laser pulse, which would occur

after 100.0 ms. The camera shutter duration was 20 ms and the intensifier gate duration was 50 ns.

A Hadland delay generator inserted a controlled delay between the initiating flashlamp signal and the ignition spark. If the delay was too long, the flame would fill the measurement region when the image was taken. The delay was progressively shortened until the exposure captured an image of the leading-edge flame-front.

With a stoichiometric mixture, the time required by the flame to travel from the spark plug to the measurement region was well defined at 23 ± 1 ms. Thus, a delay of 77 ms was required. With a lean-limit mixture, the travel time was 30 ± 5 ms, causing large variations in the flame position in the images.

6.2.5 Image sets.

Images were taken immediately downstream of the obstruction for both lean-limit (FAR = 6.55 %) and stoichiometric (FAR = 10.46 %) mixtures for a range of flame maturity, grouped as "early", "intermediate" and "late" images. For each stoichiometry and flame maturity, 50+ OH-PLIF images were obtained, along with background calibration images.

6.3 Image correction.

Before the images could be analysed quantitatively, corrections had to be made for various systematic errors (Seitzman and Hanson, 1993) :

1. dark current,
2. background noise, including non-fluorescence laser scatter,
3. variations in laser light intensity across the sheet,
4. variations in pixel response,
5. absorption of laser power across images,
6. trapping of fluorescence by OH between the laser sheet and the camera.

Such corrections were important in minimising the error of the quantitative analysis.

6.3.1 Dark current.

Dark current was caused by thermally generated signals that mimic incident radiation, i.e. build up of charge on the CCD array due to ambient heat energy near the array. It was uniform throughout an image.

In a modern CCD camera, the dark current might be 10^5 electrons/pixel/second at room temperature, but 0.1 electrons/pixel/second for a Peltier cooled camera at 200 K, such as the one used for the DPIV experiments (Chapters 3-4). The camera used for the OH-PLIF experiments was water cooled, but the dark current was sufficient to saturate the array in 45 seconds. The array was reset immediately prior to an ignition, to minimise the dark current to approximately 100 counts.

For each image, the actual contribution from dark current could be found from the signal count in a region where there was no laser induced signal and then subtracted from all pixels in the image.

6.3.2 Background noise.

Background noise artificially raised the signal level in the image. It was caused by ambient illumination, such as flame luminosity and non-LIF scattered laser light. Since the intensifier gate time was approximately 50 ns, the amount of ambient illumination detected by the CCD camera could be neglected.

Non-LIF scattered laser light was caused by spurious scatter from solid objects in the laser sheet path and Rayleigh scatter from the premixture. The sources of spurious scatter were the top edge of the turbulence generating grid and the windows in the laser path. Scatter from the grid was minimised using black tape. In most cases, such scatter was in a different part of the image from the flame-front OH signal, so did not affect the measurements. Scatter from the windows was small compared with the fluorescence signal, since the edges of the field of view were 25 mm from each window. Since the wind tunnel contained no micron sized particles such as droplets, there was no Mie scatter background.

Ten background calibration images were taken with the laser sheet passing through the premixture, without ignition. The mean of these images (with dark current subtracted) was used to correct the experimental OH-PLIF images.

These laser related sources of noise in the PLIF images could be avoided by collecting off-resonant PLIF, i.e. from a higher wavelength. This would require a laser system that could pump a transition to a sufficient degree for non-resonant PLIF to give a useful signal level.

6.3.3 Flatfielding.

Laser sheets do not usually have uniform intensity profiles. From a Nd:YAG laser source, the profile will be close to Gaussian. Hence, the signal at the edge of the sheet will be lower than that at the centre, due to the reduced local laser fluence.

The response of each pixel on the CCD array to the signal incident on the front plate of the intensifier will not be uniform throughout the array. This variation, which is typically constant over long periods of time, will be dominated by variations in gain of up to 30 % in the intensifier.

To correct the PLIF images for both of these factors, each experimental image with background and dark current subtracted was divided by a normalisation image. This procedure is termed "flatfielding".

Ideally, the normalisation image would consist of a fluorescence image of a uniform species concentration with the same spectral distribution as the signal fluorescence. Variations in signal throughout the normalisation image would be due only to the variations in the laser sheet profile and pixel response. Tait (1994) produced a normalisation image for OH-PLIF images using a uniform field of acetone. In the case of the wind tunnel images, the laser power of 10 mJ per pulse was insufficient to give a fluorescence signal from an expanded laser sheet.

An alternative normalisation image was obtained by imaging Mie scatter from a uniform particle field. The turbulence grid was removed and the wind tunnel was pumped with very dilute quantities of smoke particles to produce a uniform field from which the Mie scatter of the laser light could be imaged. Ten images of Mie scattering from the smoke particles and three background images were taken. The normalisation image was generated by subtracting the dark current and background noise from the

Mie images and taking the mean. The flatfielding, dark current and background correction process is shown in Fig. 6.4.

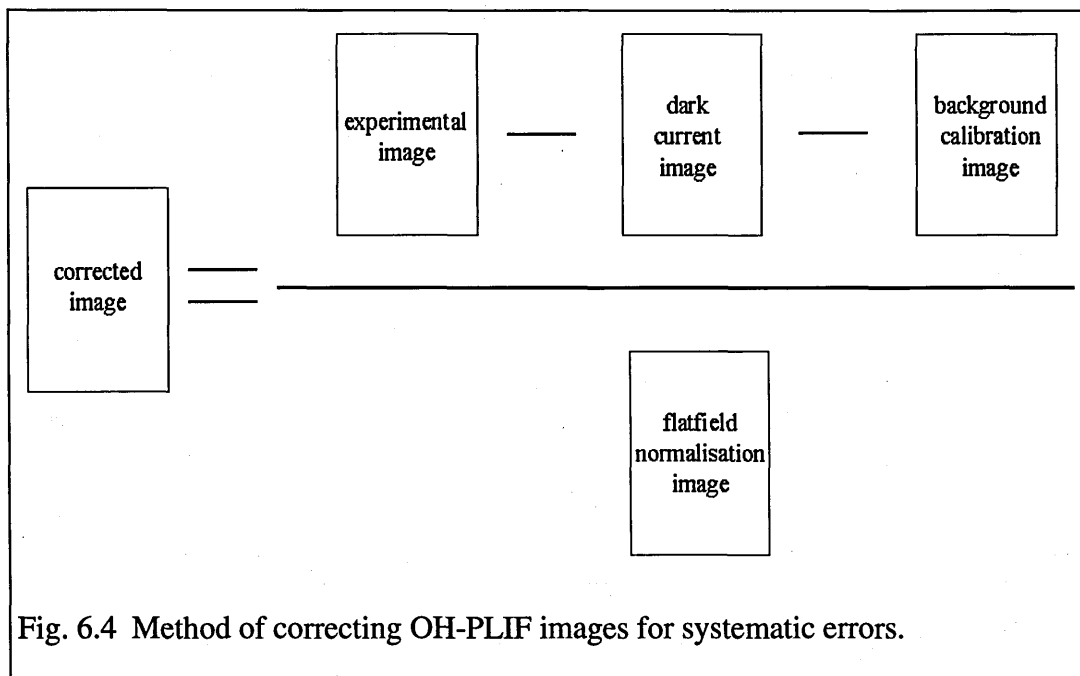
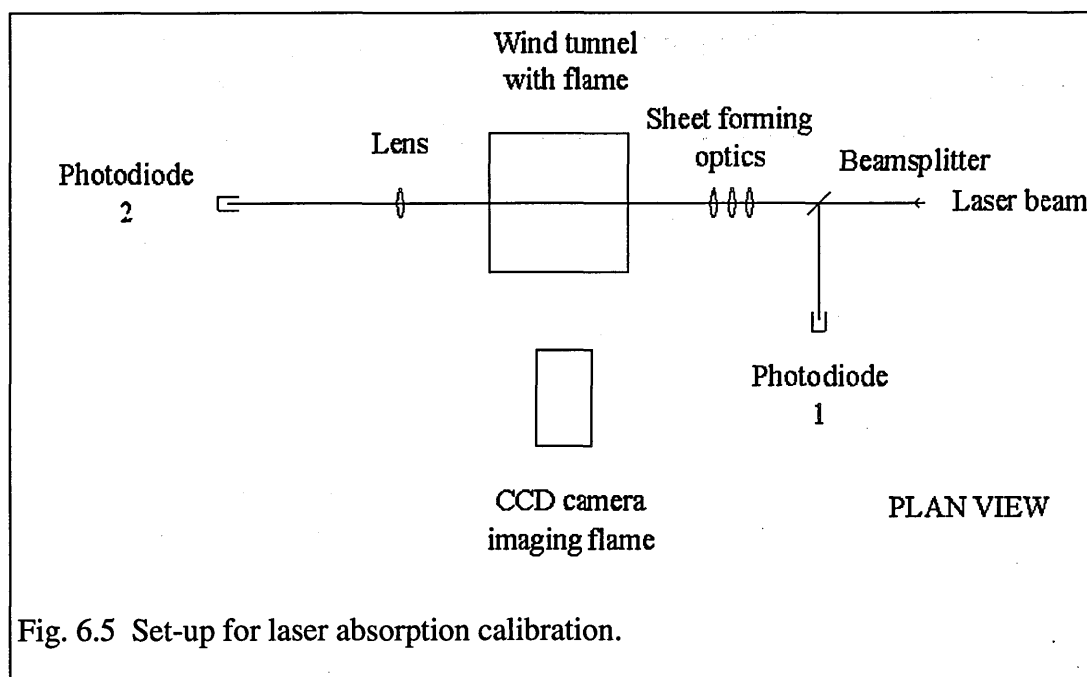


Fig. 6.4 Method of correcting OH-PLIF images for systematic errors.

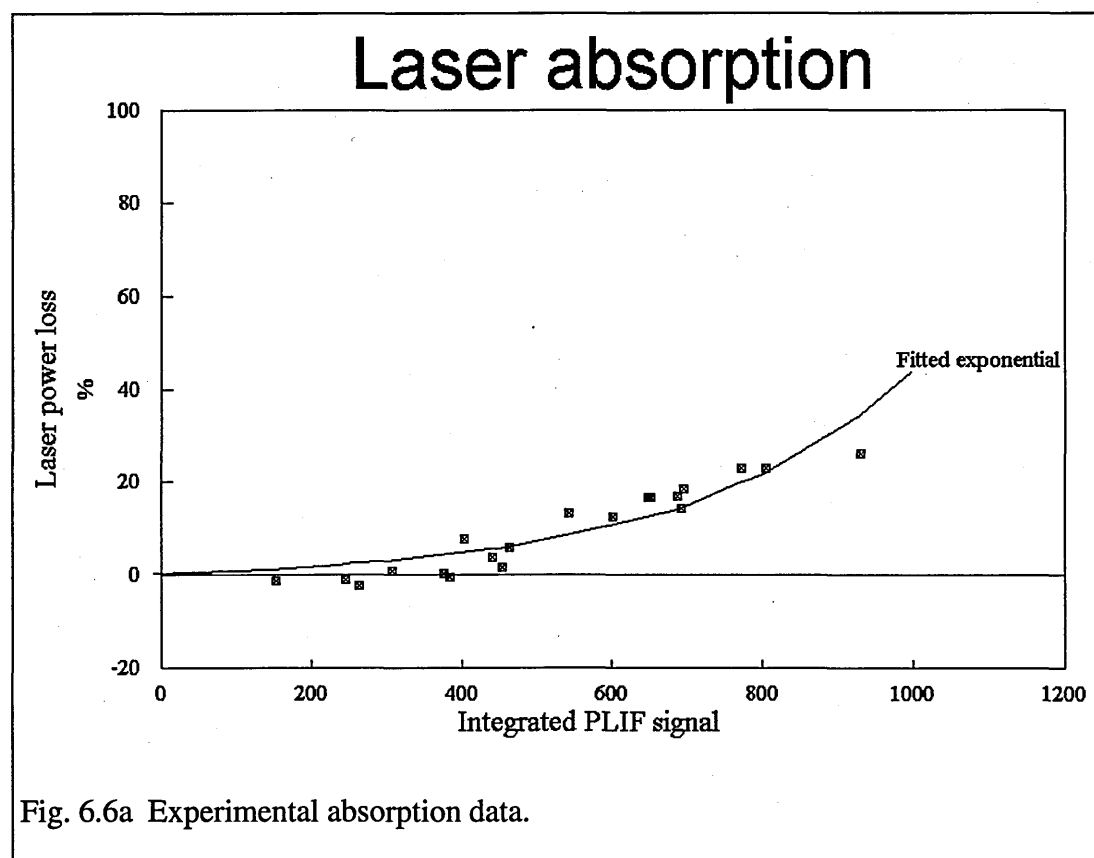
6.3.4 Laser absorption.

As the laser pulse in the form of a sheet travelled through the flame, energy was lost as it excited OH radicals, so that the energy at the "far side" of the flame was lower than at the "near side". This is termed laser absorption or attenuation (Seitzman and Hanson, 1993), and the degree of absorption varied across the height of the sheet, according to the total number of OH radicals in the path of each part of the laser sheet. To correct for laser absorption, the average absorption for each image was taken from a calibration curve, then each horizontal line was corrected using an iterative calculation (Hertz and Aldén, 1987).

To create the absorption calibration curve, the laser beam was sampled before and after the wind tunnel by reflecting a small fraction of the beam onto previously calibrated photodiodes, as shown in Fig. 6.5. A series of measurements of photodiode signal were taken alternately with no flame and with a stoichiometric flame in the wind tunnel. It proved impractical to make such measurements with a lean-limit stoichiometric flame due to the fluctuations in the time from ignition to the flame being present in the measurement region.



For each ignition, an image was taken of the OH-PLIF. The signal intensity volume integral for each image was taken as a measure of the amount of absorbing OH present. The fractional power loss across the wind tunnel, taken from the photodiode measurements was plotted against the OH signal integral. An exponential curve was fitted to the data in accordance with the Beer-Lambert law of laser absorption (Quagliaroli, 1993) and is shown in Fig. 6.6a. The data taken with no flame in the wind tunnel confirmed the consistency of the measurements.



Since the field of view contained two out of four gaps in the turbulence generating grid, it was assumed that the power loss across an image was half that measured by the photodiodes, which were sampling the whole width of the wind tunnel. Thus, a calibration curve for the power loss due to laser absorption for stoichiometric mixtures was created (Fig. 6.6b). Using a computer model of methane combustion (developed by J. Warnatz at Stuttgart University), it was found that the equilibrium OH concentration for lean-limit ignitions was 47.3 % of the value for stoichiometric ignitions, giving the second calibration curve in Fig. 6.6b.

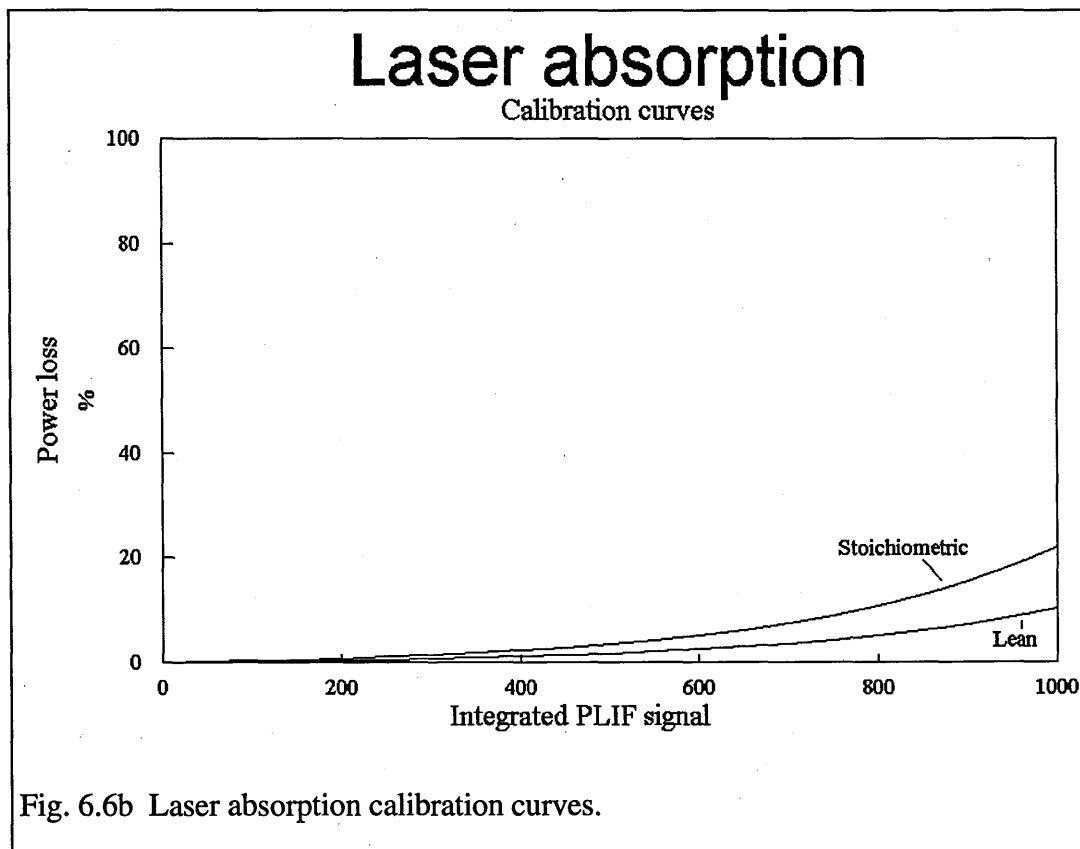


Fig. 6.6b Laser absorption calibration curves.

For each experimental image, the signal volume integral was measured and the appropriate calibration curve used, to give the estimated total power loss due to laser absorption across the image. For most images, the loss was of order 5 %. Each horizontal line in the image was then processed separately. The intensity integral of the line was found as a fraction of the total intensity integral of the image from which the fractional signal loss in the line was calculated. The signal along the line was then corrected, using the method of Hertz & Aldén (1987). Essentially, the signal was enhanced iteratively until the theoretical laser absorption calculated from the corrected signal agreed with the measured absorption.

The laser-independent LIF signal $u(x)$ is given by :

$$u(x) = \frac{f(x)}{I_{\text{rel}}(x)} = C\sigma N(x) \quad (6.1)$$

where $f(x)$ is the experimental LIF profile, $I_{\text{rel}}(x)$ is the relative laser power, $I(x)/I_0$, $N(x)$ is the number density of OH radicals, σ is the absorption cross-section, C is a constant, including many experimental factors.

The Beer-Lambert law gives the laser beam attenuation as :

$$I_{\text{rel}}(x) = \exp\left[-\int_0^x \sigma N(x') dx'\right] \quad (6.2)$$

$$\text{with } I_{\text{rel}}(L) = T \quad (6.3)$$

from the experimental measurements of the fractional transmitted power, T .

To initialise the algorithm, $I_{\text{rel}}(x)$ is assumed to be unity in Eq. (6.1). The first approximation for the laser-independent LIF signal is then $u^1(x) \approx C\sigma N(x)$.

If this expression is substituted into Eq.(6.2), and C is found from the boundary value in Eq. (6.3), the following expression is obtained :

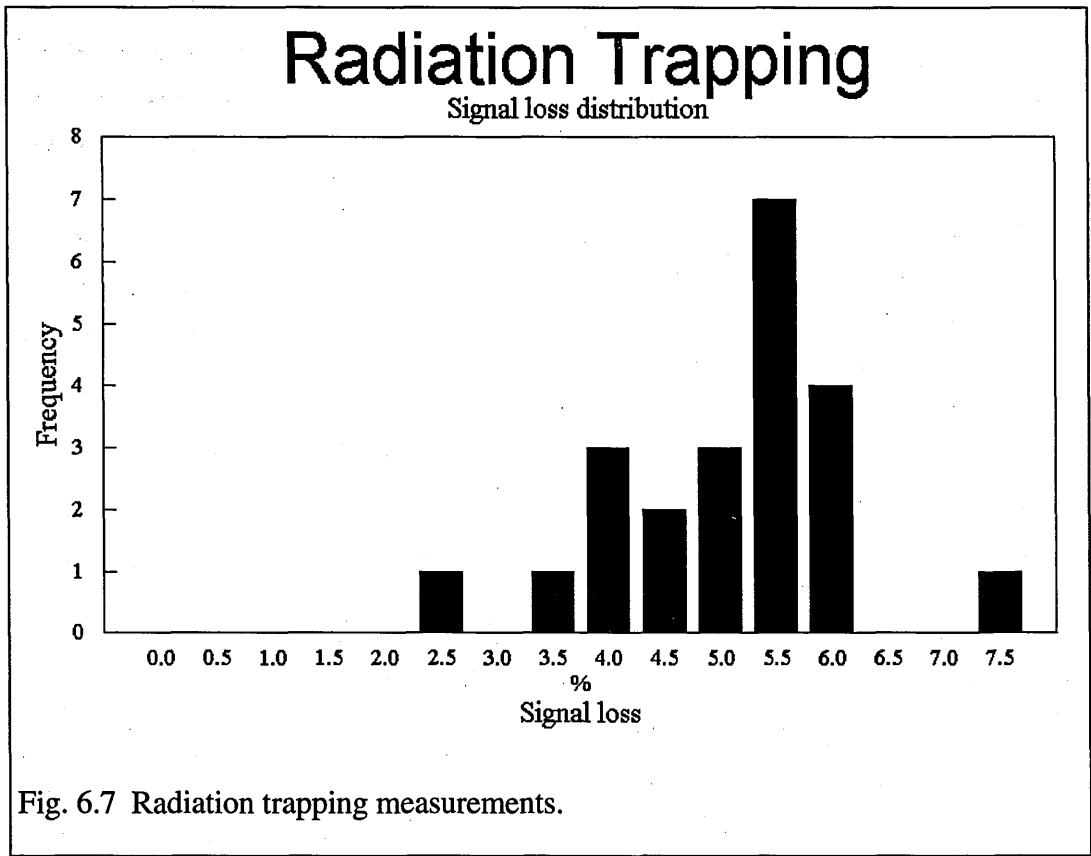
$$u^n(x) = \frac{f(x)}{\exp\left[\frac{\int_0^x u^{n-1}(x') dx'}{\int_0^L u^{n-1}(x') dx'} \ln(T)\right]} \quad (6.4)$$

The iteration was repeated until it converged, usually after ~5 iterations. The algorithm was valid for highly absorbing media, though in most cases the absorption was less than 5 %.

6.3.5 Radiation trapping.

Radiation trapping (Seitzman and Hanson, 1993) or self-absorption (Üngüt et. al., 1993b) is a term used to describe the absorption of fluorescence by the OH radicals between the laser sheet and the camera.

The mean loss of signal due to radiation trapping was measured with a calibration experiment. The laser sheet was directed through a Bunsen burner flame, placed behind the wind tunnel. PLIF images of OH in the Bunsen flame were taken with no flame in the wind tunnel and with the tunnel filled with a stoichiometric flame, coincident with the laser pulse. These images were taken alternately to reduce the variation in conditions. The reduction in signal due to radiation trapping by the flame in the wind tunnel was calculated for each pair of images. The loss was quite consistent, shown in Fig. 6.7, with a mean of 4.8 %, r.m.s. 1.0 %. It was not possible to know the structure of the signal loss due to radiation trapping in each individual image, so a correction could not be made to the images for this source of noise.



6.3.6 Collisional quenching.

The OH-PLIF signal will typically be reduced due to excited radicals losing energy in collisions with other molecules (Eckbreth, 1988; Seitzman and Hanson, 1993). There is *electronic quenching*, in which an excited radical is de-excited back to the ground state and *rotational quenching*, in which it is redistributed to another rotational level, from which to relax to the ground state, possibly through fluorescence. Section 5.4.2 described how the correction for collisional quenching generally involves knowing the partial pressures of all species present other than the one of interest, the rates for deactivation of the species of interest by all other species present, and the dependence of these rate constants on temperature. These parameters were not measured for this experimental arrangement and data for this particular excitation line does not appear in the literature.

Reported investigations of collisional quenching rates of the $Q_1(3)$ line at 308.154 nm showed that in the burnt gases of hydrocarbon-air flames, the total quenching rate is essentially constant (Bergano et. al., 1983; Schwarzwald et. al., 1987). In the flame-front, both quenching efficiencies (Garland and Crosley, 1986) and gas density decrease with increasing temperature. Becker et. al. (1990) calculated the effect of such variations on the combustion of propane-air mixtures in an engine simulator. They estimated that the net effect was a maximum error of 10 % of the fluorescence signal, in pressures of between 14.5 and 22 bar. At atmospheric pressures, the collisional quenching should be much less. Therefore, the error due to variations in collisional quenching throughout each experimental image was not expected to be greater than 10 %.

6.4 Qualitative properties of OH-PLIF images.

Visual inspection of the OH-PLIF images of the rapidly expanding atmospheric methane-air flame revealed several noteworthy features. In the images shown in Figs. 6.10-6.15, the fluorescence signal is displayed using the arbitrary, linear, false colour scale shown, where black and blue represent low signal levels, red and white represent high signal levels. The thresholding was chosen as carefully as possible in order to illustrate these features without artificially mis-representing the OH concentrations. Each image was taken from a different ignition event.

6.4.1 OH concentration profiles.

Throughout the images, the three main regimes of OH radical concentration, referred to in Section 5.2.6 were evident :

- zero levels (black) in the unburnt gas,
- equilibrium levels (dark blue, black) in the burnt gas,
- super-equilibrium levels (green, yellow, red, white) at the flame-front.

This is illustrated in Fig. 6.8, which shows the cross-section of the fluorescence signal along BB' in the image in Fig. 6.10a. At either edge of the profile is the unburnt region. The fluorescence signal and hence OH concentration is very low, at less than 500 counts. The signal rises sharply at the flame-front before it peaks at 3400-3800 counts, 10-15 pixels inside the flame-front. The super-equilibrium OH region typically extended for 20-30 pixels from the start of the reaction zone, which corresponded to 2.3-3.5 mm. Inside the flame-front, the OH fluorescence signal level decays to the equilibrium level, of order 2200 counts. Variations of signal in this equilibrium region could be due to variations in burnt gas temperature, radiation trapping (see 6.3.5) or quenching of the fluorescence (see 6.3.6).

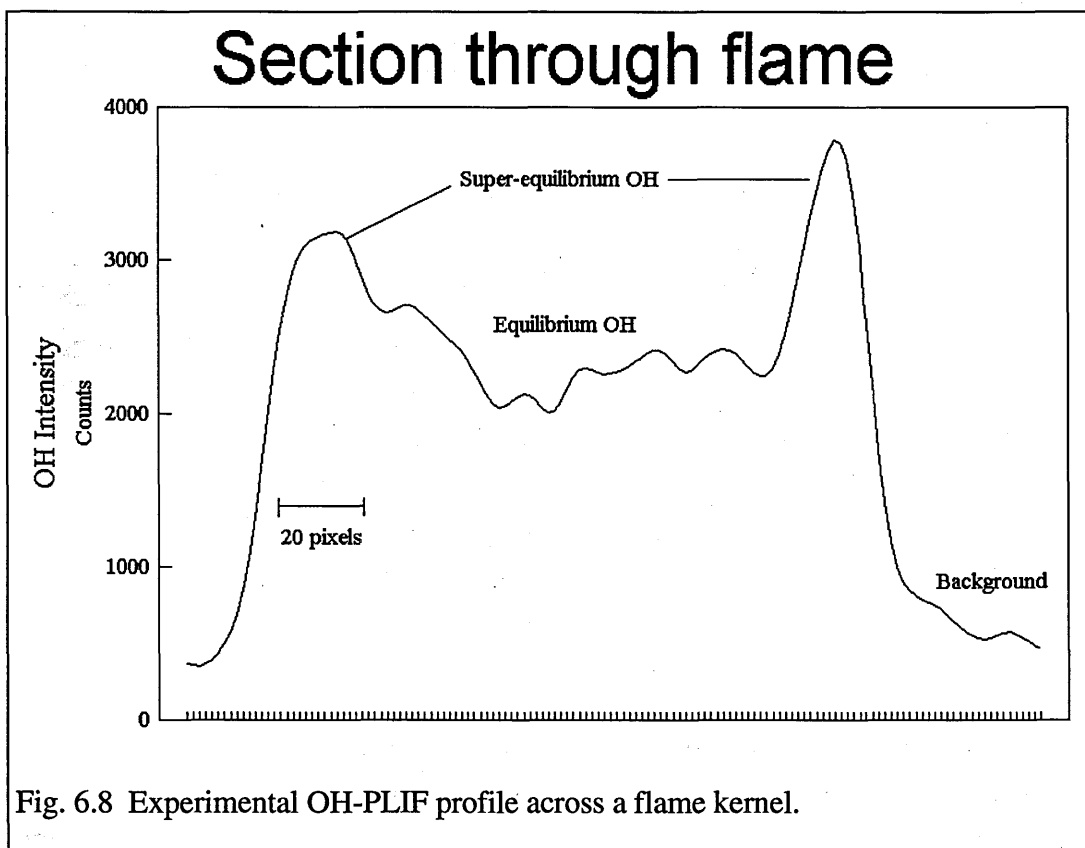


Fig. 6.8 Experimental OH-PLIF profile across a flame kernel.

6.4.2 Discontinuous signal regions.

Many of the images contain examples of discontinuous regions of fluorescence signal, for example region 19 in Fig 6.10e. Most of these regions are likely to be fingers of flame, where the connecting region is out of the plane of the laser sheet. This situation is illustrated in Fig. 6.9. The flame in Fig. 6.9a has a complicated shape. If the laser sheet were introduced in plane AA', with the fluorescence imaged from the right, the experimental OH-PLIF image would look something like Fig. 6.9b, which contains separated regions of OH. However, these regions are part of a continuous flame, connected out of the plane AA'.

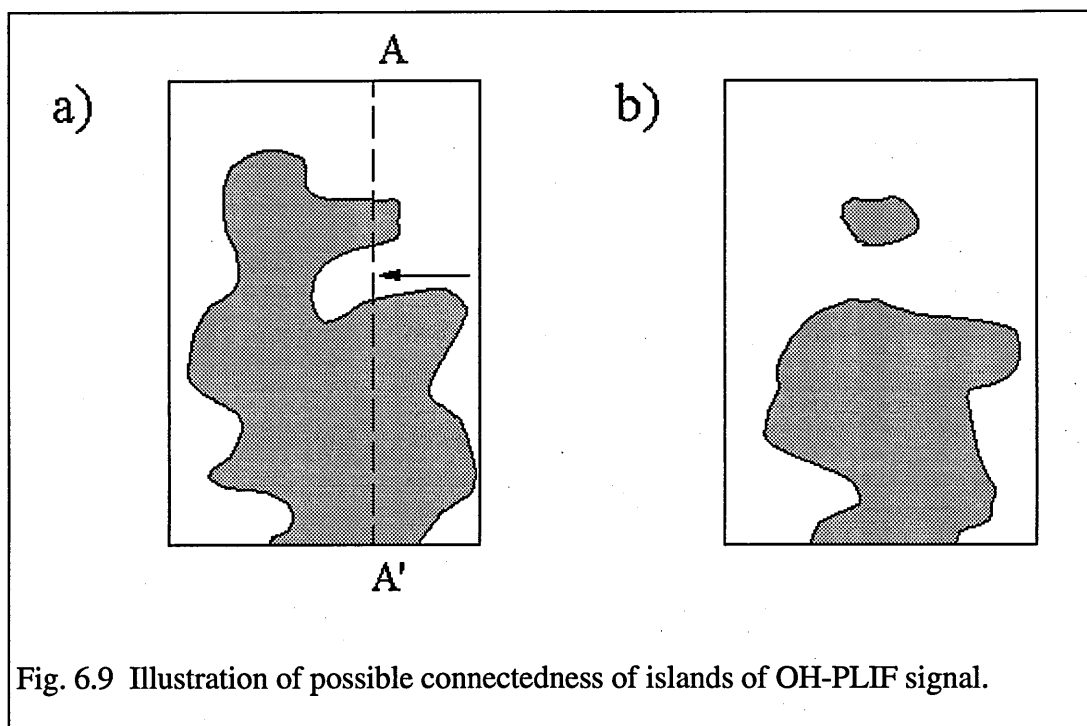


Fig. 6.9 Illustration of possible connectedness of islands of OH-PLIF signal.

It has not been clearly established whether truly discontinuous burning regions exist. It may be possible that in extremely high turbulent strain regions, thin flame necks can be quenched so that part of the flame is separated from the bulk of the flame to create a separate burning region. At the point of separation, the neck would be characterised by equilibrium or sub-equilibrium OH levels due to suppression of the turbulent burning rate. Region 20 (Fig. 6.11e) may be a candidate for a flame neck about to be quenched. Alternatively, the laser sheet may have been at the edge of the flame, with an adjacent parallel plane containing the super-equilibrium levels of the flame-front.

The possible existence of this phenomenon could be determined by performing experiments with multiple parallel sheets, to give the OH concentration over a three-

dimensional region (Yip et. al., 1988; Frank et. al., 1991; Patrie et. al., 1994), discussed in Section 5.4.5.

6.4.3 Variation of burning rate.

The value of the maximum super-equilibrium OH fluorescence signal varied at different parts of a flame-front, implying variation in the reaction rate. Some variations may be due to uncorrected noise, such as radiation trapping or collisional quenching (see Sections 6.3.5 and 6.3.6). However, these variations were expected to be at the 5-10 % level.

Where variations occurred, visual inspection revealed that areas of the flame-front with convex curvature had higher signal due to enhanced local burning rates, while those with concave curvature had suppressed burning rates. (The definition of curvature types are from the perspective of the burnt region, as shown in Fig. 5.2.)

Examples of convex flame-front burning rate enhancement are shown in regions 1-4 in Fig. 6.10, while examples of concave flame-front burning rate suppression are shown in regions 5-8 in Fig. 6.10. There were no examples of the opposite trend. An attempt to clarify this feature quantitatively is discussed in Section 6.5.3.

For atmospheric pressure methane-air mixtures at 300 K at the lean-limit stoichiometry, the Lewis number is less than unity (Griffiths and Barnard, 1995). The discussion in Section 5.2.3 described how in this situation, the diffusivity of deficient reactants (in this case methane molecules) is greater than the heat diffusivity. This leads to convex flame-front regions having enhanced burning rates, whilst concave sections have suppressed burning rates.

It was not certain in these OH-PLIF images whether variations of burning rate at the flame-front were due to curvature effects, or different degrees of strain on the flame-front, which might cause the same trend. Simultaneous measurement of the strain rate would allow this question to be addressed more completely.

6.4.4 Quenched regions.

A potentially significant feature which was occasionally seen in the images is shown in region 9 in Fig. 6.10e. At the boundary between an unburnt gas region, with near zero fluorescence signal and a burning region, a super-equilibrium signal would be

expected, corresponding to the laminar flamelet. However, in this example, the fluorescence signal at the boundary is at the level of the equilibrium OH of the burnt gas region.

Possible explanations of this and similar features in terms of the image generation are :

1. Low local pixel response. However, these features occur all over the CCD array, so this can be discounted.
2. Low local laser fluence due to uncorrected laser absorption. Downstream (to the left) of many of these features is a region of high signal level, so this can be discounted.
3. High local radiation trapping. This unlikely since it would imply that there were high OH levels in the line of sight of these features, but not in adjacent areas that exhibit high fluorescence signals.
4. The plane of the laser sheet was parallel to the edge of the flame and half-way between the super-equilibrium level and the zero background level of OH.

Another possibility is that the local turbulence strained the flame-front so much that the flame became locally quenched, i.e. the local burning rate was zero. This resulted in only equilibrium OH levels (or even sub-equilibrium OH levels) corresponding to the local temperature field. This possibility was discussed in Section 5.2.4 and has been predicted by models of turbulent premixed combustion and recognised in work by Becker et. al. (1990), Lockett (1995).

6.4.5 Experimental OH-PLIF images.

The qualitative features of the experimental images are described for the different flame maturities, for both stoichiometries. The influence of turbulence on the flames downstream of the grid varied due to the difference in flame speed between the lean-limit and the stoichiometric flames. The spark to grid time of the stoichiometric flames was generally 21-22 ms, giving a mean flame speed of 10.7 m/s, while for lean-limit flames it was 28-30 ms, giving a mean flame speed of 7.9 m/s. This meant that the

stoichiometric flames encountered a more rapid expansion as they burst through the obstruction. They were subject to more intense flame stretch and possibly cooling effects. In contrast, the lean-limit flames suffered less flame stretch, but would have been burning less strongly, so were more easily quenched.

6.4.5.1 Lean-limit stoichiometry images.

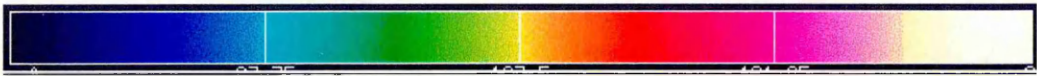
Figs. 6.10-6.12 show a selection of images of lean-limit flames. Fig. 6.10 shows flames shortly after they burst through the grid. In each image, there are two distinct flame kernels corresponding to the two grid gaps in the field of view. The earliest flames (Figs. 6.10a-6.10e) generally have a continuous super-equilibrium OH boundary, corresponding to an unbroken flame-front, then decay of fluorescence signal toward equilibrium levels in the burnt gas region. The flame-fronts for these very early images are fairly smooth, before interaction with the turbulence.

Slightly later images (Figs. 6.10f-6.10p) show flames subject to stretch due to the turbulence. This causes flame-front wrinkling to occur, which leads to complicated kernel shapes. Islands of OH start to appear (see 6.4.2), which could be separate burning regions but are more likely to be fingers of flame, connected in a different plane.

As the flame-front becomes more wrinkled, the trend for convex regions to have enhanced burning rates (regions 1, 2, 3, 4) and for concave regions to have suppressed burning rates (regions 5, 6, 7, 8) becomes more marked. This is consistent with the curvature effect of a flame with Lewis number less than unity (see 5.2.3). However, since the strain rate at the flame-front was not known for these flames, the effect of the turbulent flame stretch on the local mass burning rate is not known. There are also examples of apparent flame quenching, for example regions 9, 10, 11, 12.

Fig. 6.11 shows lean-limit flame images that have developed further. The flames have become very wrinkled, eventually causing the two flame kernels to coalesce (Fig. 6.11e-6.11i). Fig. 6.11d shows many islands of OH signal, which are also to be found in almost all images of flames of this maturity. The burning rate-curvature trend can be seen in all the images in Fig. 6.11.

Regions 13, 14, 15, 16 show parts of flame-fronts where the boundary fluorescence signal is at the same absolute level as the equilibrium regions. This implies that the local burning rate was small, if not zero, i.e. the flame was quenched at that



False colour scale for Figs. 6.10-6.15

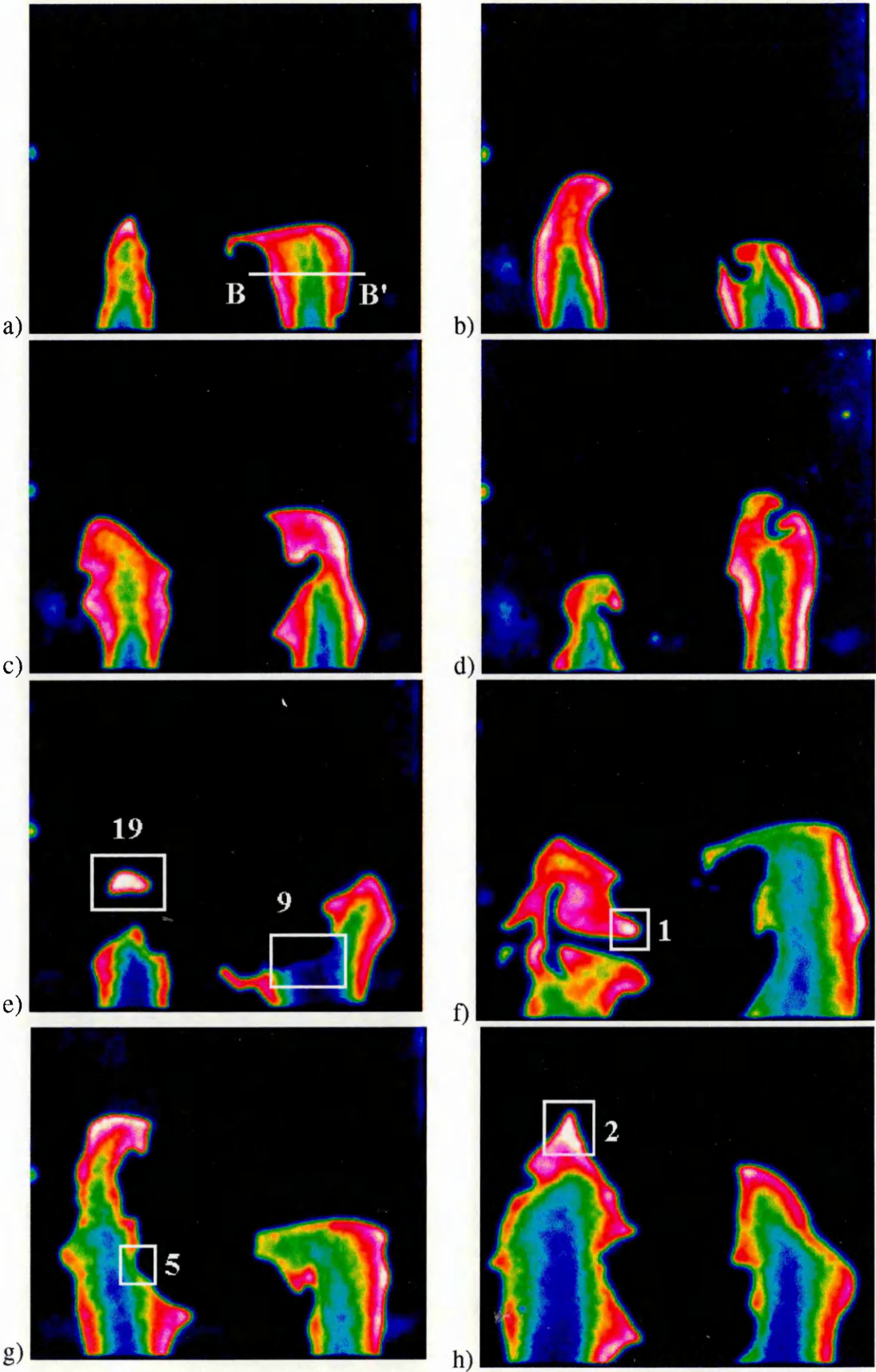


Fig. 6.10a-h OH-PLIF images of early lean-limit flames.

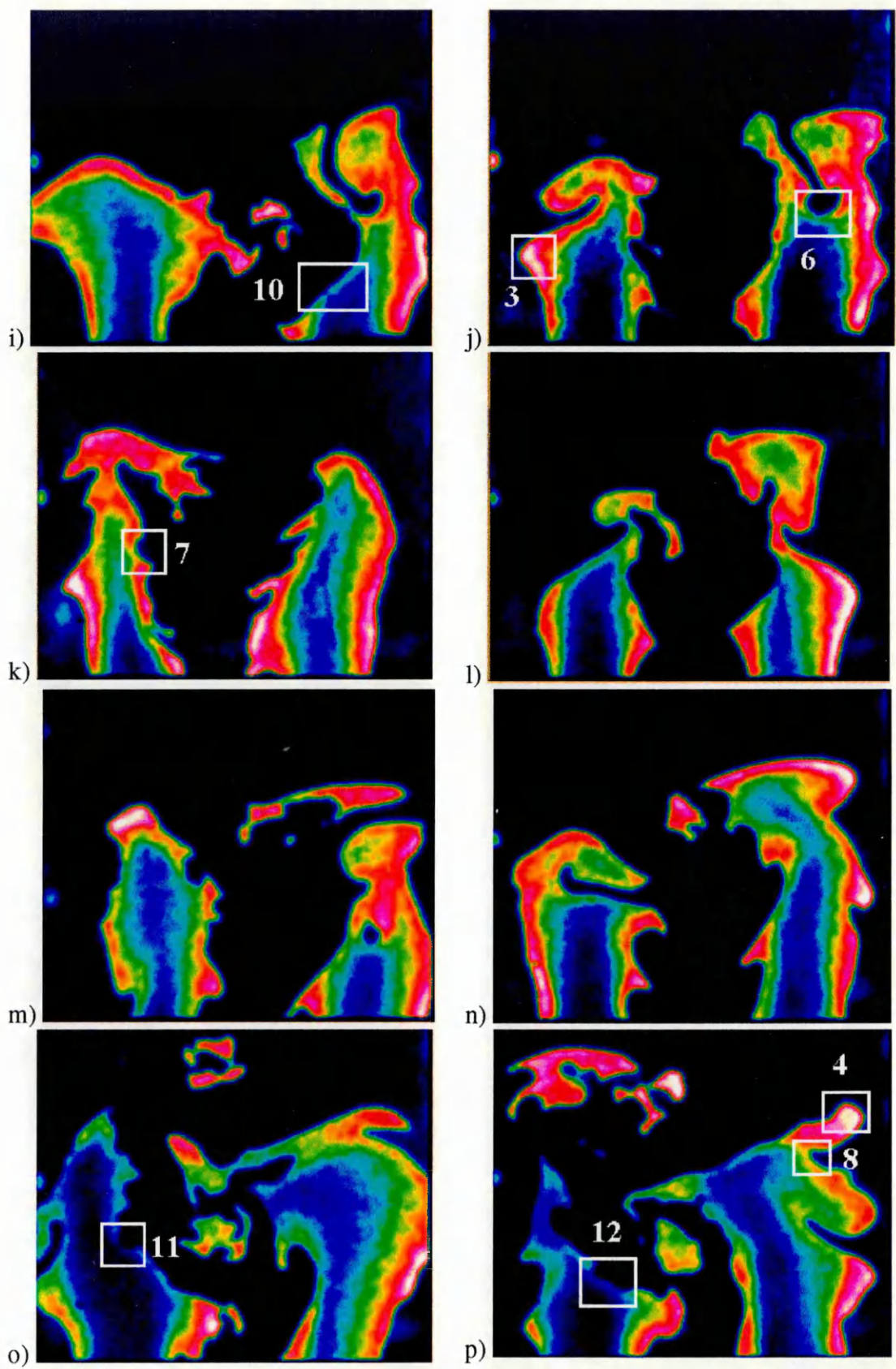


Fig. 6.10i-p OH-PLIF images of early lean-limit flames.

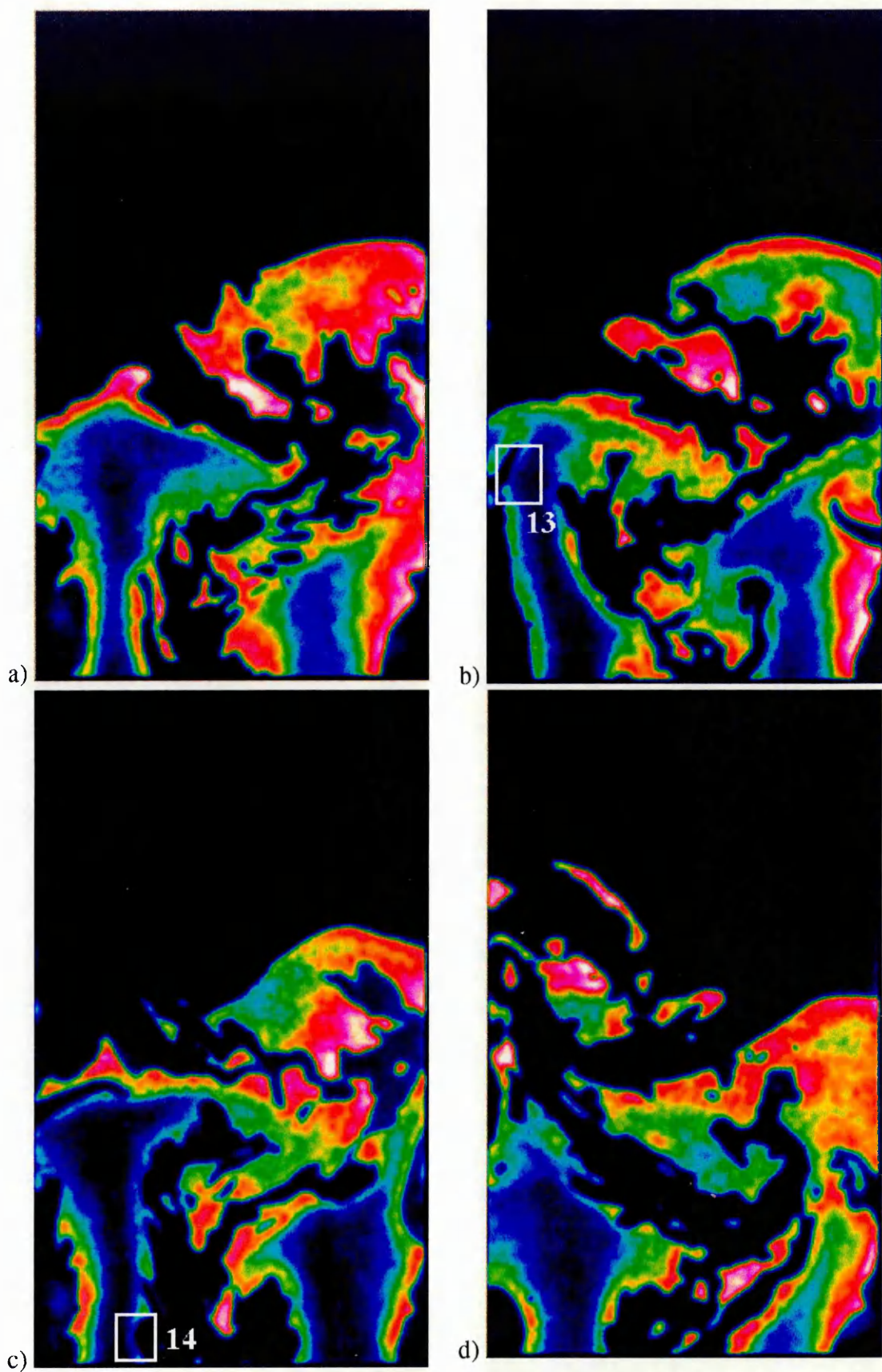


Fig. 6.11a-d OH-PLIF images of intermediate lean-limit flames.

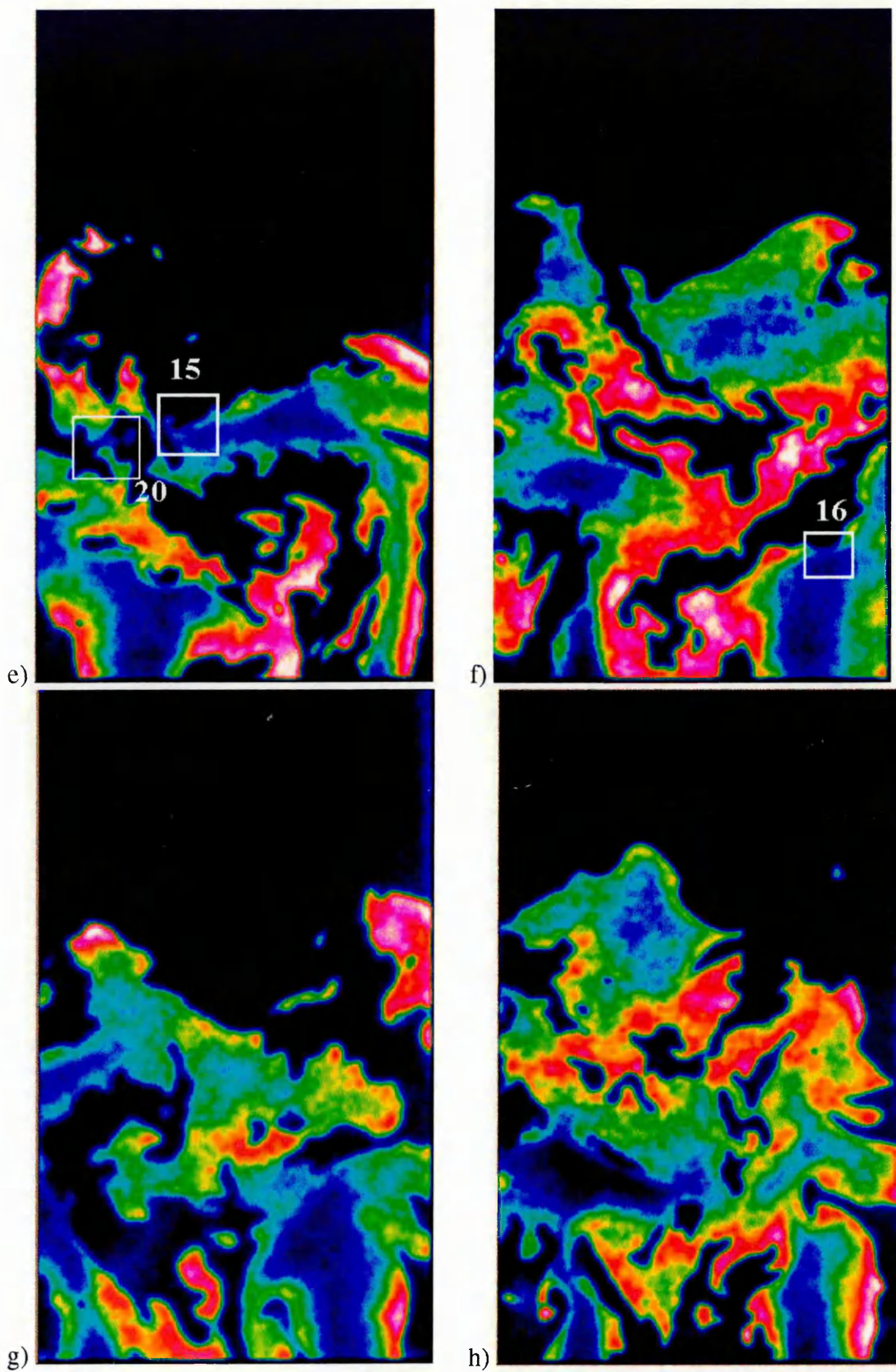


Fig. 6.11e-h OH-PLIF images of intermediate lean-limit flames.

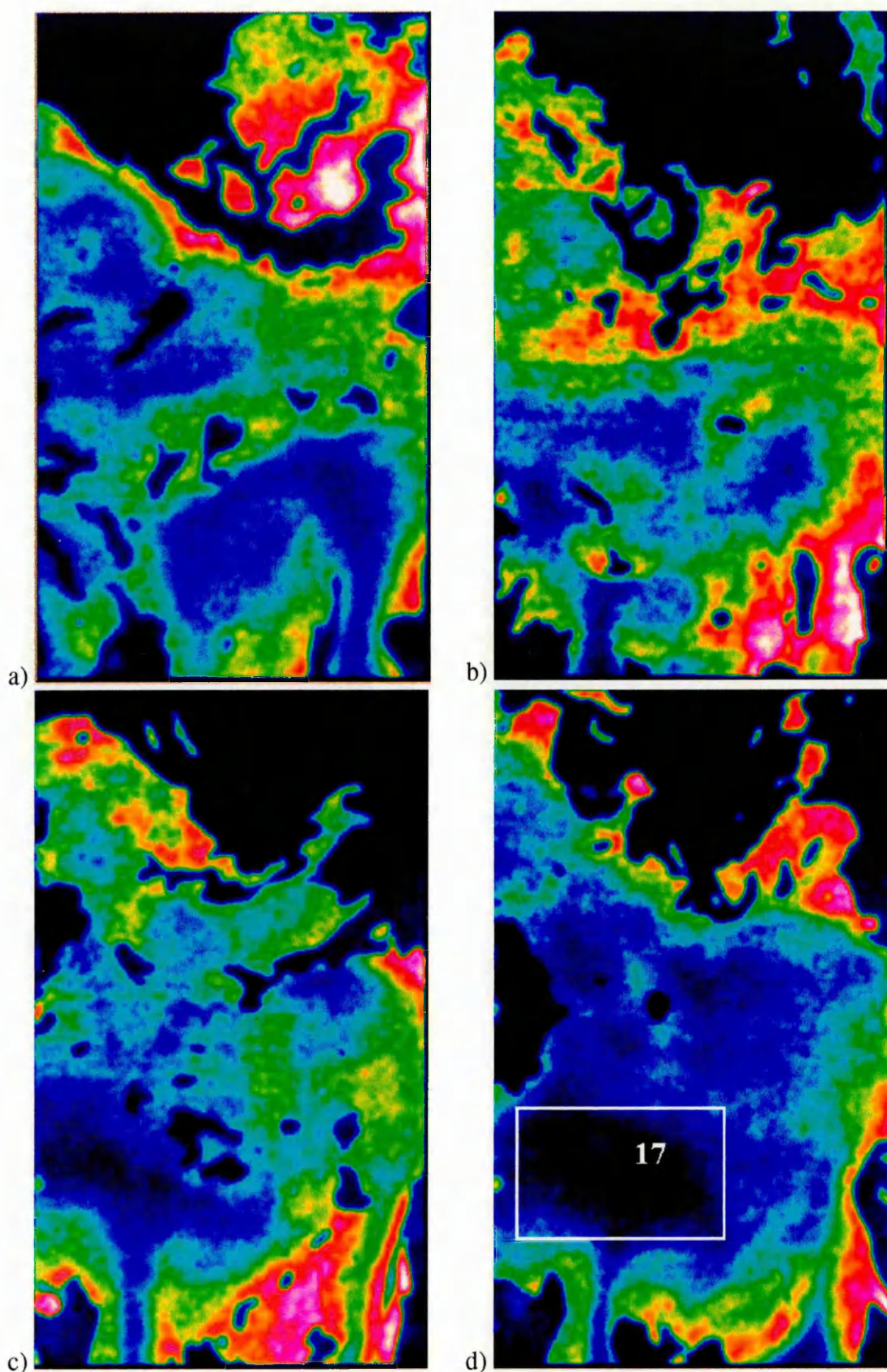


Fig. 6.12a-d OH-PLIF images of late lean-limit flames.

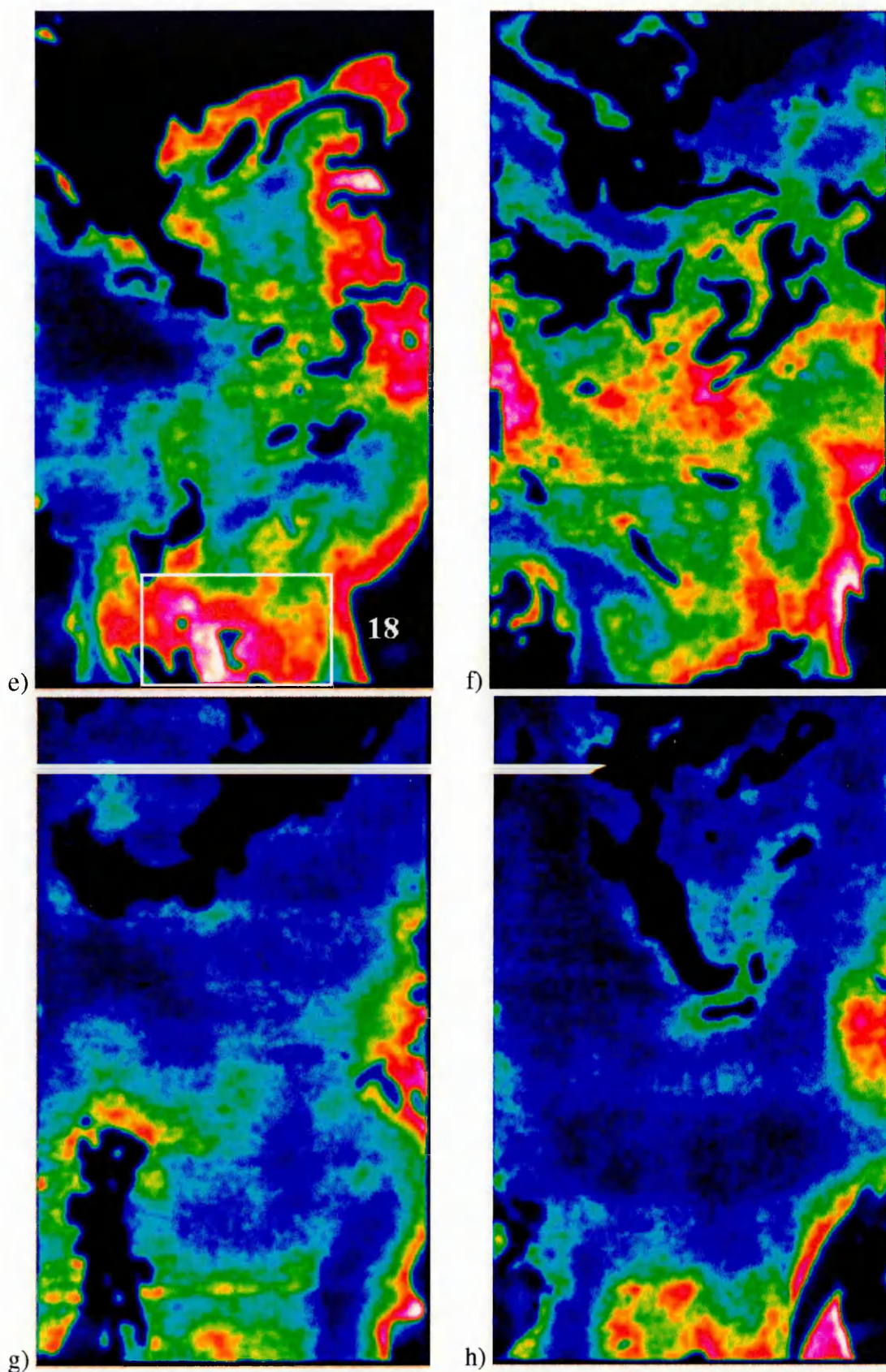


Fig. 6.12e-h OH-PLIF images of late lean-limit flames.

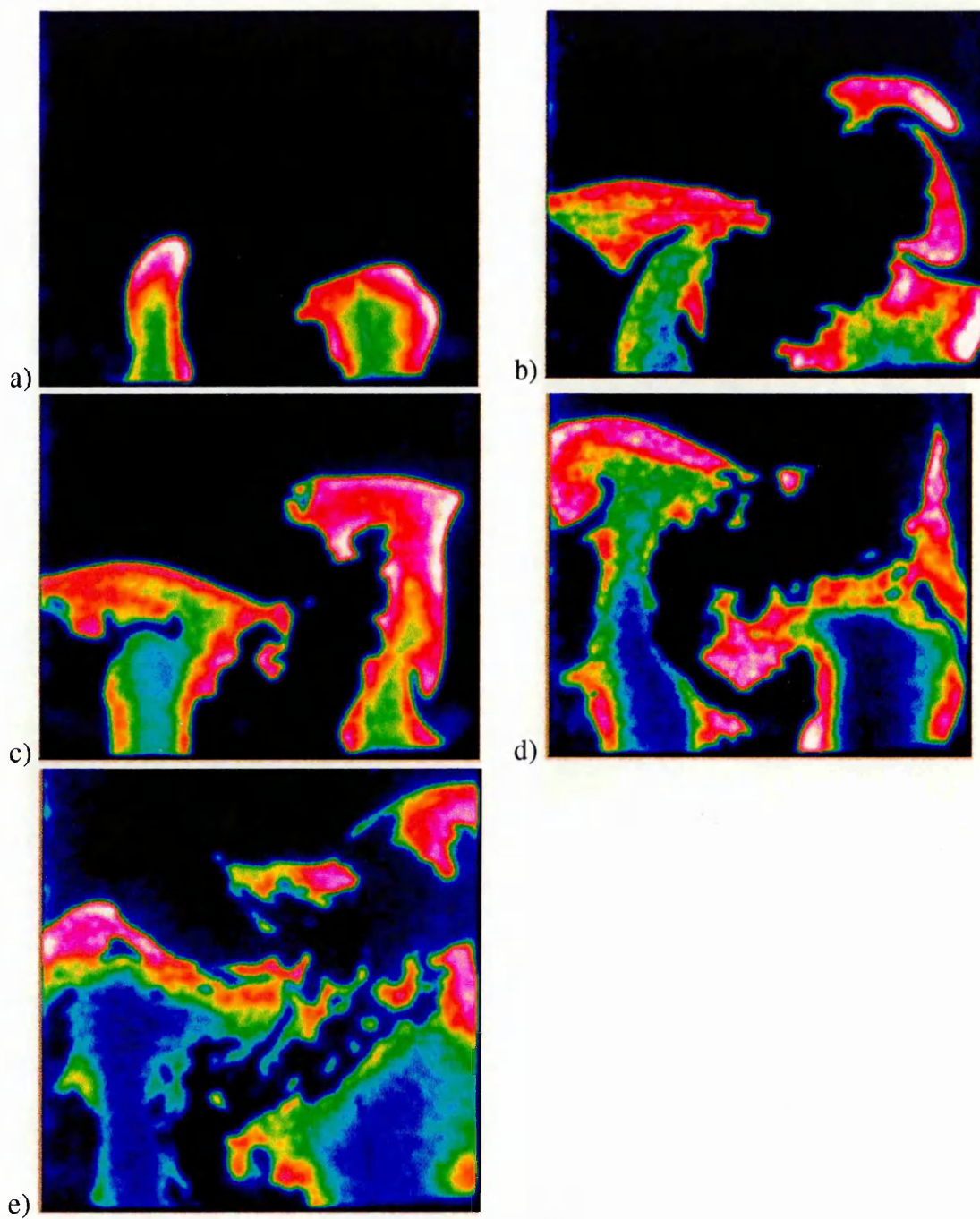


Fig. 6.13a-e OH-PLIF images of early stoichiometric flames.

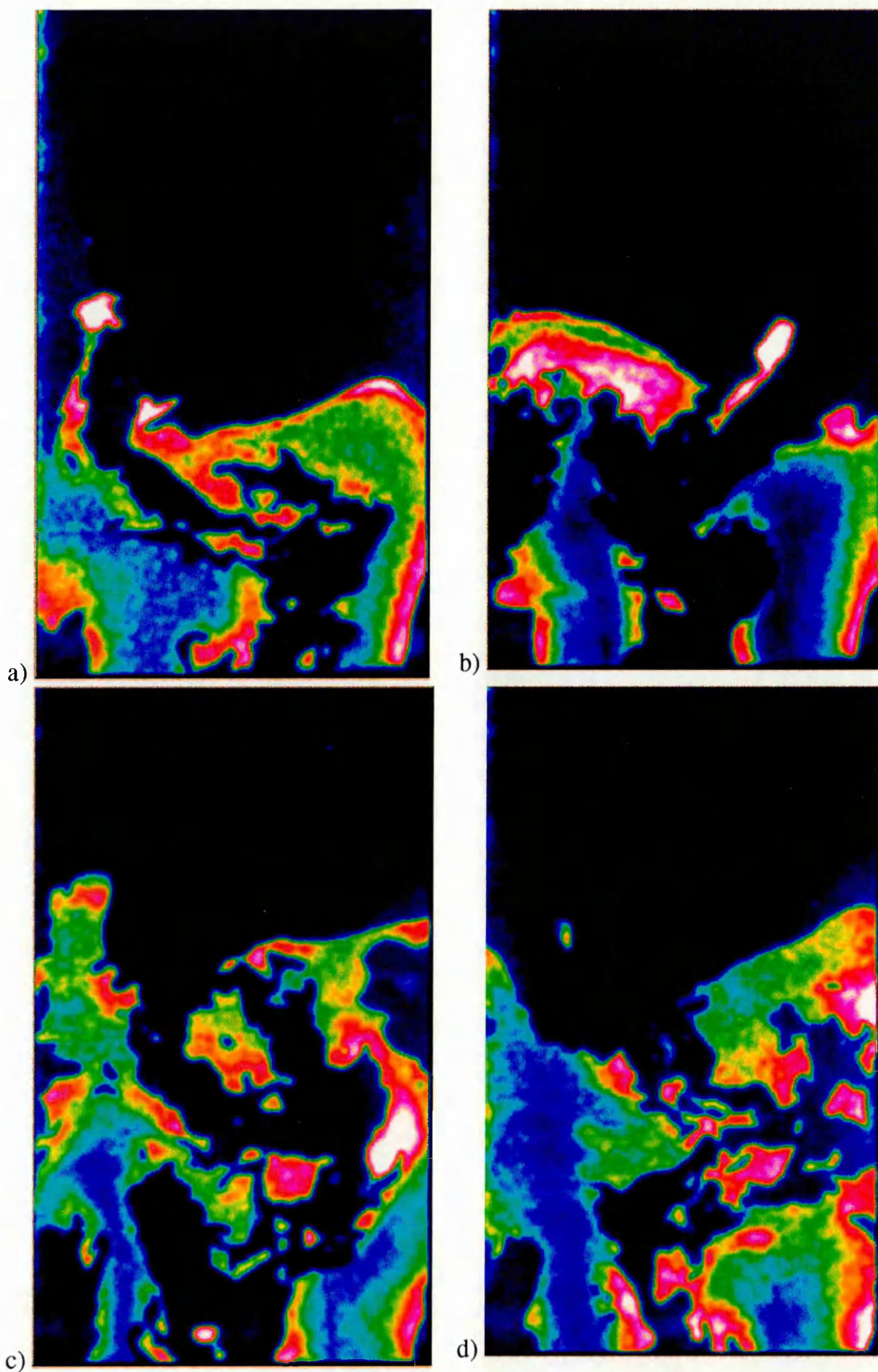


Fig. 6.14a-d OH-PLIF images of intermediate stoichiometric flames.

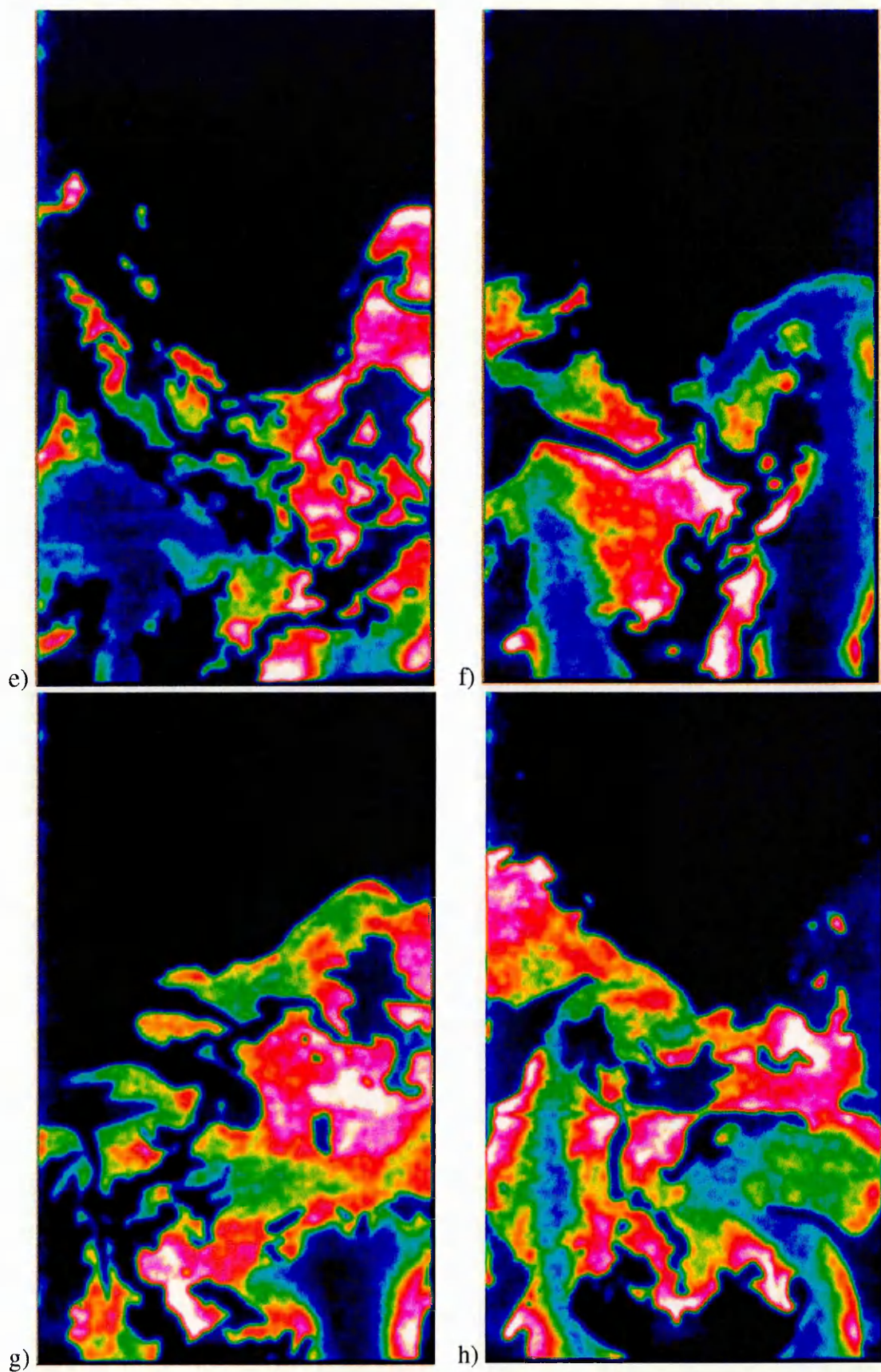


Fig. 6.14e-h OH-PLIF images of intermediate stoichiometric flames.

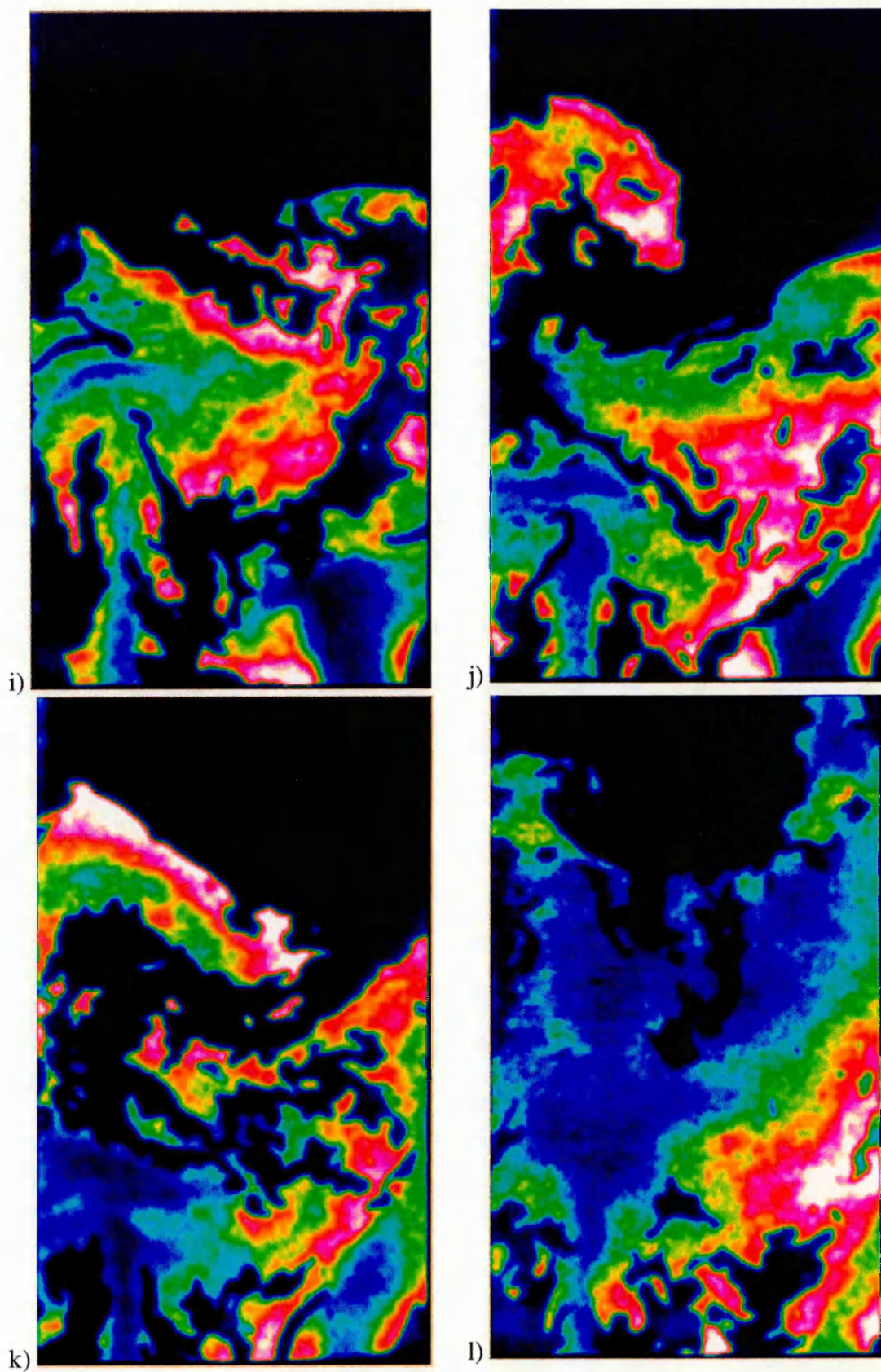


Fig. 6.14i-l OH-PLIF images of intermediate stoichiometric flames.

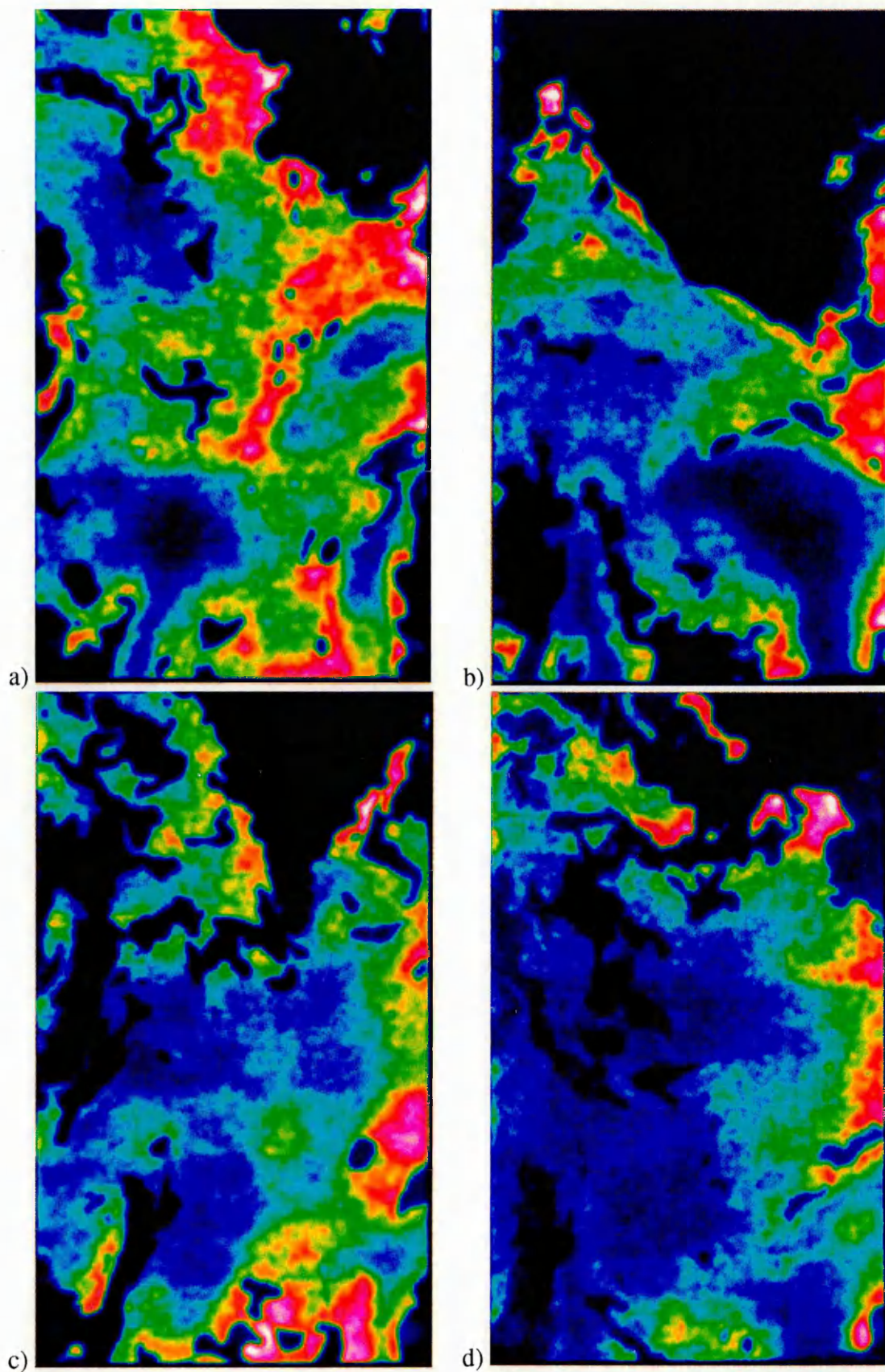


Fig. 6.15a-d OH-PLIF images of late stoichiometric flames.

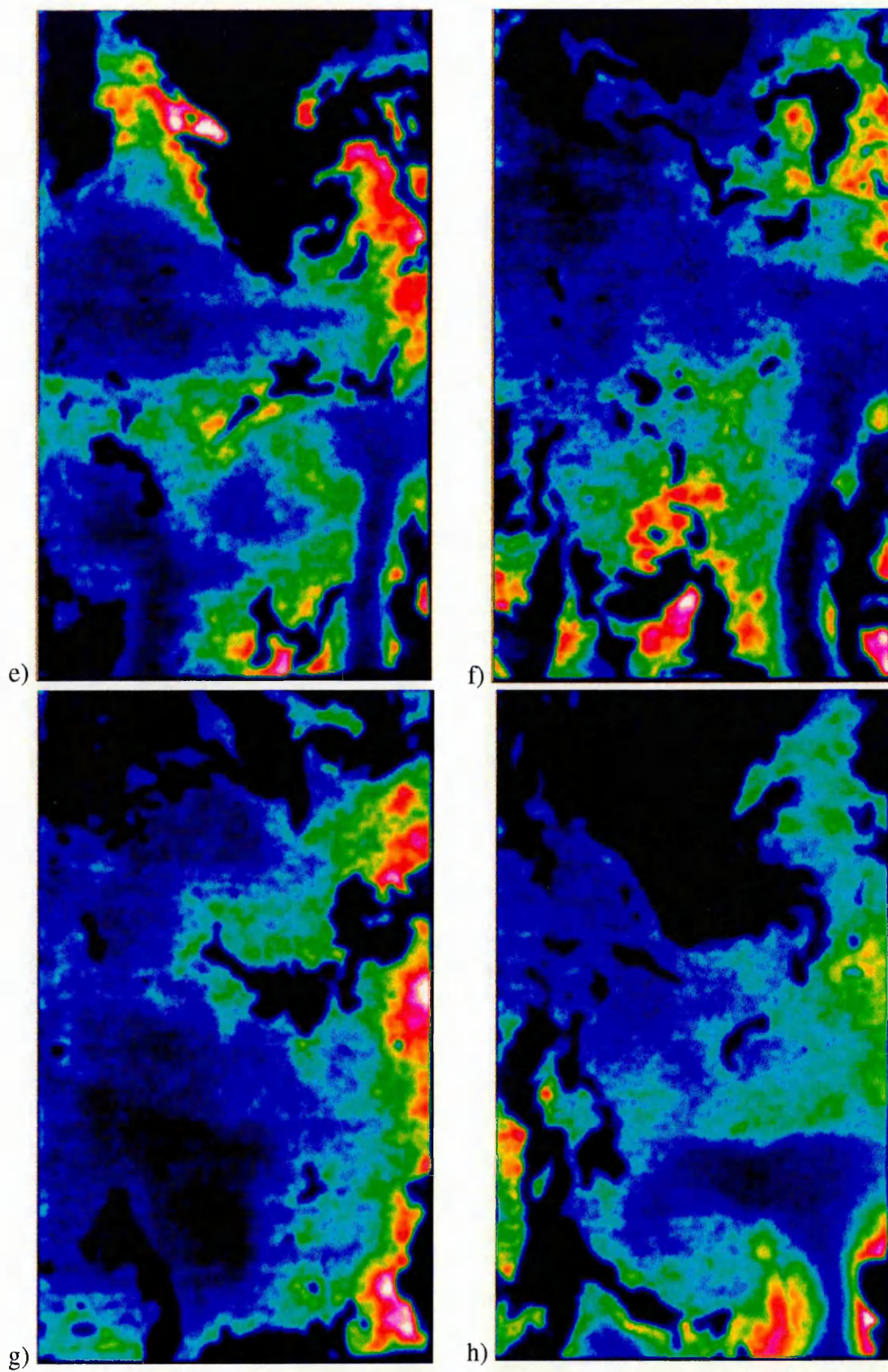


Fig. 6.15e-h OH-PLIF images of late stoichiometric flames.

position, due either to extreme curvature effects or high flame stretch. Apparent flame-quenching is more common with these images of more mature flames.

Fig. 6.12 shows images of lean-limit flames where the flame-front has reached the top of the field of view. Most of the image is filled with hot burnt gases (equilibrium OH levels), which cool over time. Region 17 appears to be an area of combustion products that have cooled such that the OH signal level is very low. Combustion occurs in the wake of the central grid rod after the main flame-front has travelled downstream. Region 18 is a good example of this feature.

In these later flames, some of the flame-front continues to burn at a high rate, whilst other regions appear to be quenched. In Figs. 6.12a-6.12e, the leading flame-fronts contain many red-white regions, indicating continued strong burning rates, whilst in Figs. 6.12f-6.12h, the leading flame-fronts show blue fluorescence signal, though other areas within these images are burning strongly. Assuming these low signal levels are not artefacts (see 6.4.4), they indicate that it is highly probable that by this maturity of flame (60 mm downstream of the grid), the flame has become significantly, if not completely quenched by the turbulence induced strain rate.

6.4.5.2 Stoichiometric images.

OH-PLIF images from flames with stoichiometric premixture are shown in Figs. 6.13-6.15. The features of these images are very similar to those described for the lean-limit images above.

Fig. 6.13 shows flames shortly after bursting through the grid. Wrinkling of the flame-front becomes more pronounced as the flame starts to interact with the turbulence, leading to complex flame-fronts, variations in the burning rate correlated to curvature and some quenched regions.

Fig. 6.14 shows flames of "intermediate" maturity. The degree of wrinkling is often greater than for the equivalent lean-limit flames, due to the greater strain rates. These images show many examples of islands of OH and quenched flame-fronts, particularly Fig. 6.14l

Some images of flames from stoichiometric premixtures where the flame-front has reached the top of the image are shown in Fig. 6.15. There is continued burning in the grid wake after the flame-front has travelled downstream. Some flame-fronts are

burning strongly (Figs. 6.15a-6.15e), whilst others appear to be quenched (Figs. 6.15f-6.15h).

6.4.5.3 Comparison.

There is no clearly visible difference in the properties of the lean-limit and stoichiometric flames. This implies that, although the lean-limit flames would have been more susceptible to flame quenching because of their lower burning rates, the more rapid expansion of the stoichiometric flames through the grid leads to higher flame stretch rates for these flames.

Thus, both types of flames are likely to suffer significant flame quenching by the time the principal flame-front has reached the top of the field of view, 60 mm downstream of the obstacle.

6.5 Quantitative analysis.

More detailed analysis of these experimental OH-PLIF images included extraction of the inner cut-off of the flame-fronts, giving the smallest scale of wrinkling and correlation of super-equilibrium OH signals at the flame-front with the local curvature.

6.5.1 Image region discrimination.

In order to perform flame contour and burning rate analysis on the experimental images, it was necessary to classify different regions of each image as unburnt, equilibrium OH (burnt) and super-equilibrium OH (flame-front). Since these regions were distinguished by the LIF signal strength, a thresholding method was appropriate. The fluctuations in laser power from image to image, leading to variations in signal strength were not recorded. Consequently, comparisons between the absolute pixel intensities of different images were not performed.

Fig. 6.8 illustrated that the gradient of fluorescence signal at the flame-front boundaries was very steep. In that example, the choice of a threshold between 1000 and 1500 counts would result in a variation of flame-front contour of only 3 pixels. Defining the threshold value for distinguishing equilibrium OH areas from super-equilibrium OH areas was more sensitive, since the gradient of the decay of OH concentration was more gradual. Another factor was the variation of the signal level of equilibrium OH levels throughout an image. Such variations were caused by variations in the burnt gas temperature and uncorrected variations in laser intensity, radiation trapping and collisional quenching.

6.5.1.1 Edge detection.

Initially a method was sought that would automatically determine the thresholds from the experimental images. The first approach was to investigate edge detection algorithms. Digital edge detection makes use of differential operators to detect changes in the gradients of the grey levels in an image (Blackledge, 1992). Different gradient methods used for edge detection result from attempts to find digital approximations to ∇I , where I is the signal intensity.

$$|\nabla I| = \sqrt{\left(\frac{\delta I}{\delta x}\right)^2 + \left(\frac{\delta I}{\delta y}\right)^2} = \sqrt{[\Delta_x I(i,j)]^2 + [\Delta_y I(i,j)]^2} \quad (6.5)$$

A simple implementation uses $\Delta_x I(i,j) = I(i+1,j) - I(i-1,j)$,

$$\Delta_y I(i,j) = I(i,j+1) - I(i,j-1).$$

Two other commonly used first order edge detection masks, known as Sobel and Prewitt operators operate on a larger array of pixels and are consequently less sensitive to noise. For each pixel in the image,

$$|\nabla I| = \sqrt{[\text{mask}_x \otimes I(x,y)]^2 + [\text{mask}_y \otimes I(x,y)]^2} \quad (6.6)$$

$$\begin{array}{ll}
 \text{Sobel operator :} & \text{mask}_x = \begin{array}{ccc} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{array} \\
 & \text{mask}_y = \begin{array}{ccc} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{array} \\
 \\
 \text{Prewitt operator :} & \text{mask}_x = \begin{array}{ccc} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{array} \\
 & \text{mask}_y = \begin{array}{ccc} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{array}
 \end{array}$$

Sobel operators were used to give the gradient of the intensity at each point. The flame front was shown clearly since it occurred at a sharp gradient. However, the decay from super-equilibrium OH to equilibrium OH away from the flame front was relatively slow, so it proved difficult to obtain reliable differentiation between the two regions of interest. Areas of very low intensity gradients, such as quenched regions, caused discontinuities in the Sobel images. The analysis methods were to be applied to complete flame-front contours, so the use of Sobel operators was not suitable.

6.5.1.2 Intensity histograms.

Another region discrimination method involved investigating the histogram of the pixel intensity distribution for each image. Typically, an image would contain a large number of pixels with signal of low intensity, corresponding to the background, a large number with an intensity corresponding to equilibrium levels of OH and a large number with an intensity corresponding to super-equilibrium levels of OH. There were expected to be fewer pixels at intermediate intensity levels. The idealised histogram would therefore consist of three Gaussian curves centred on the three significant intensity levels as shown in Fig. 6.16.

A program was written to fit a "sum of three Gaussians" curve to the intensity histogram from each experimental image in turn, with the aim of taking the numbers of pixels at equilibrium and super-equilibrium levels directly from the fitted curves.

It was found that too few histograms were sufficiently close to the ideal shape for the curve fitting to be meaningful. The most common reason was that the intensity levels corresponding to equilibrium and super-equilibrium OH concentrations were close compared with the spread of the distributions, so the peaks were not significantly displaced from each other. The use of the histograms as a guide to intensity levels was retained in a qualitative way.

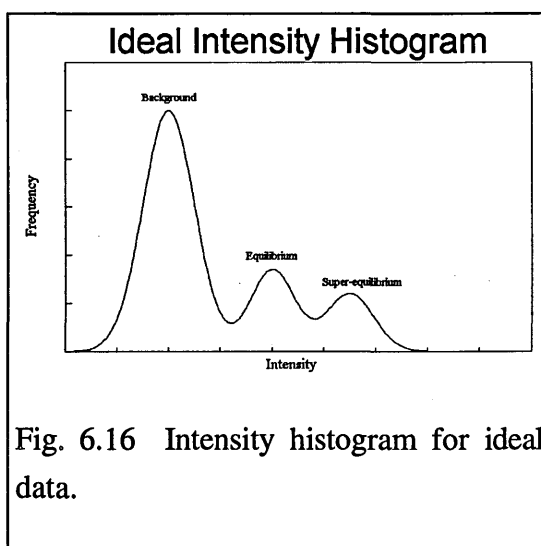


Fig. 6.16 Intensity histogram for ideal data.

6.5.1.3 Manual discrimination.

Manual thresholding was used to choose the levels corresponding to equilibrium and super-equilibrium OH concentrations by inspecting each image in turn. The principal tools used were the histogram of intensities and cross-sectional plots of significant areas of the image, such as Fig. 6.8.

When the intensity levels had been chosen, the image was redisplayed showing pixels falling within the criteria chosen, where the threshold intensity values were used to discriminate the image. This process was performed using image processing software called CLIPS, which was developed at Cranfield University by N. P. Tait. This manual thresholding method was not ideal, since it was somewhat subjective and extremely labour intensive.

6.5.2 Fractal analysis.

With the background threshold value chosen, the flame-front contour could be analysed. Using an existing program called PLIFVGA, written by A. Üngüt at Shell Research Ltd., the total perimeter of the contour was measured, with increasing step size from 2 to 60 pixels. The measured perimeter for each step size was plotted against step size on a log-log graph, which is termed the Hausdorf diagram (Üngüt et. al. 1993a).

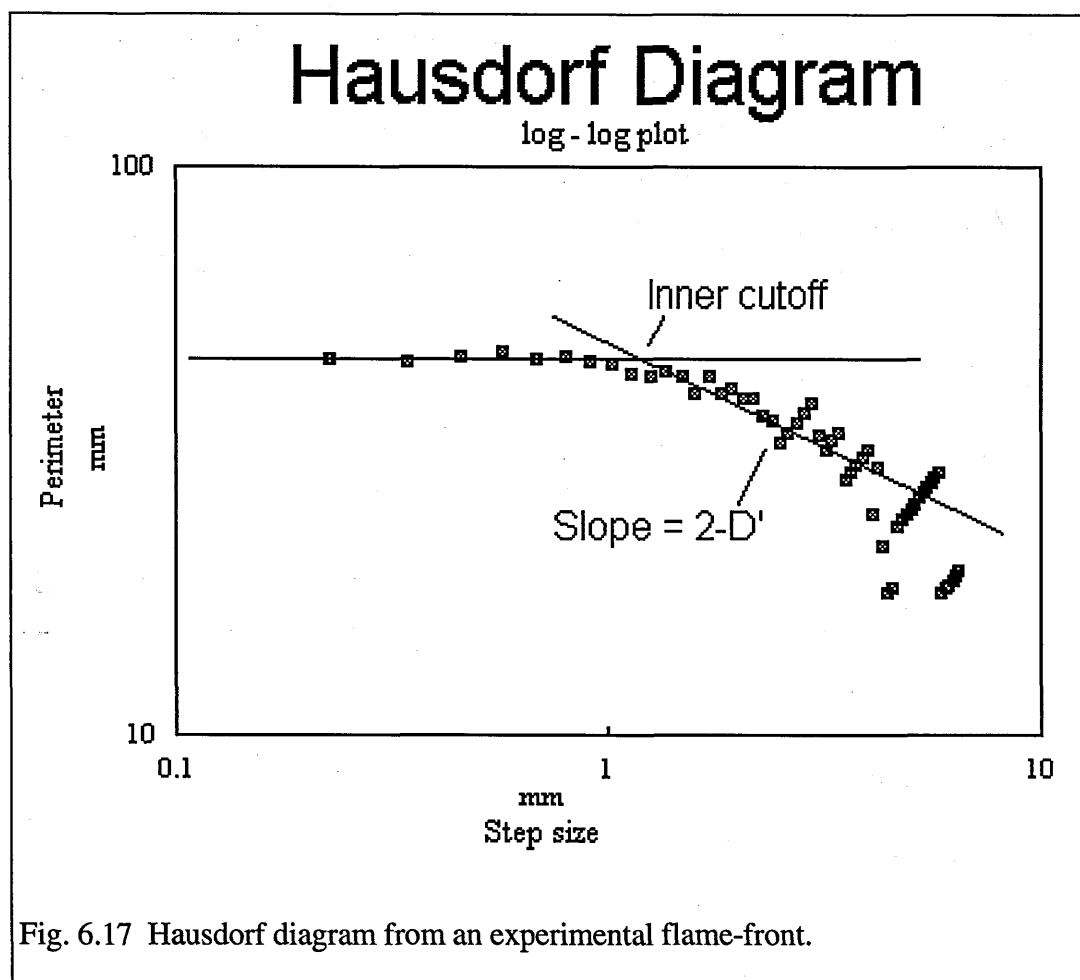


Fig. 6.17 Hausdorff diagram from an experimental flame-front.

A typical graph of one of the images is shown in Fig 6.17. It is similar to the theoretical graph in Fig. 5.3, but with a smooth variation of gradient at the inner cut-off. This was the limit of the correct measurement of the flame-front perimeter, when the step size was smaller than the smallest scale of wrinkles in the image.

For greater step sizes, the total measured perimeter dropped linearly at a rate given by the fractal dimension D' , related to the fractal dimension of the flame surface, D , by $D = D' + 1$ (Gouldin et. al. 1988). The fall in measured perimeter was because the step sizes were too large to accurately step around the perimeter; they were "cutting corners". Using the Hausdorff method, the inner cut-offs of all the OH-PLIF images were measured.

6.5.2.1 Inner cut-off distributions.

Fig. 6.18 shows the distribution of the inner cut-off for all images, and separated into images of lean-limit and stoichiometric methane-air mixtures, with mean and r.m.s. values shown in Table 6.1. Each distribution approximates to a Gaussian centred on

1.45 mm with a half width of 0.35-0.40 mm. These distributions indicate that the value of the inner cut-off did not vary significantly with the stoichiometry. The value of 1.45 mm, corresponding to 13 pixels, was three times the spatial resolution (3-4 pixels), indicating that the measurements were not resolution limited.

	<u>All</u>	<u>Lean-limit</u>	<u>Stoichiometric</u>
Mean	1.45	1.45	1.44
r.m.s.	0.38	0.40	0.35

Table 6.1 Mean and r.m.s. values of distributions in Fig. 6.18. Unit is mm.

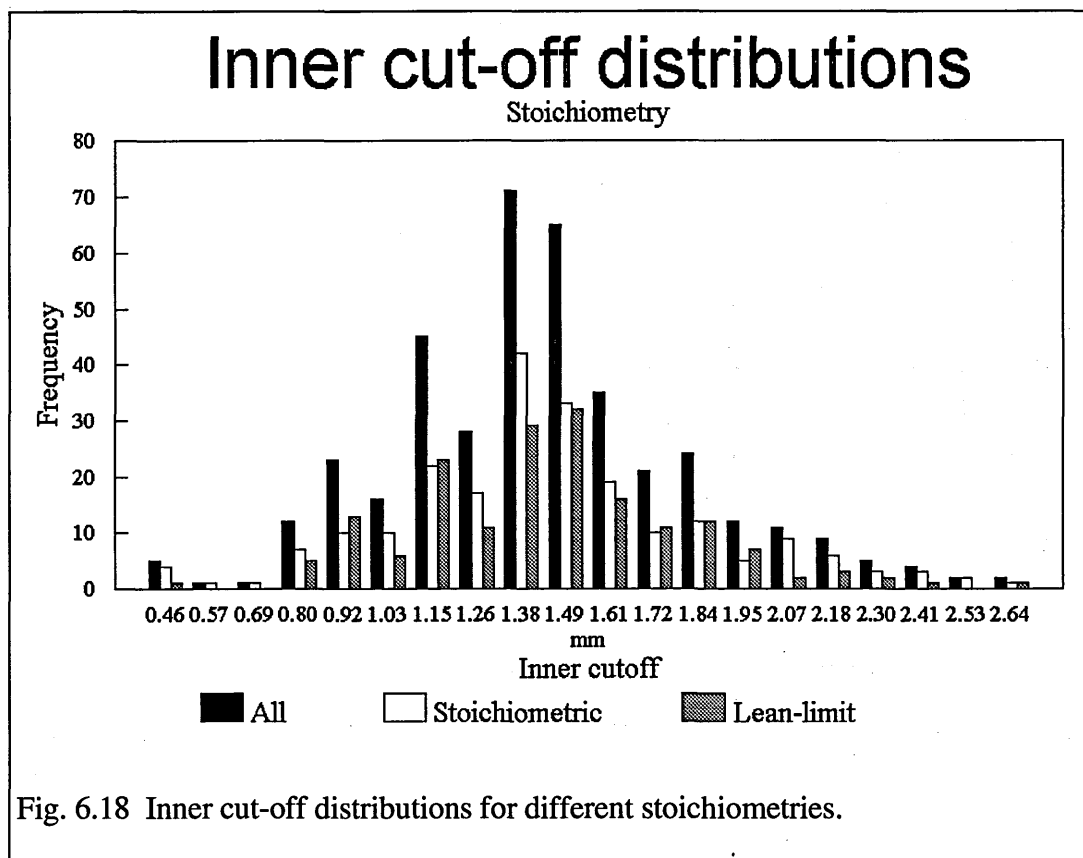


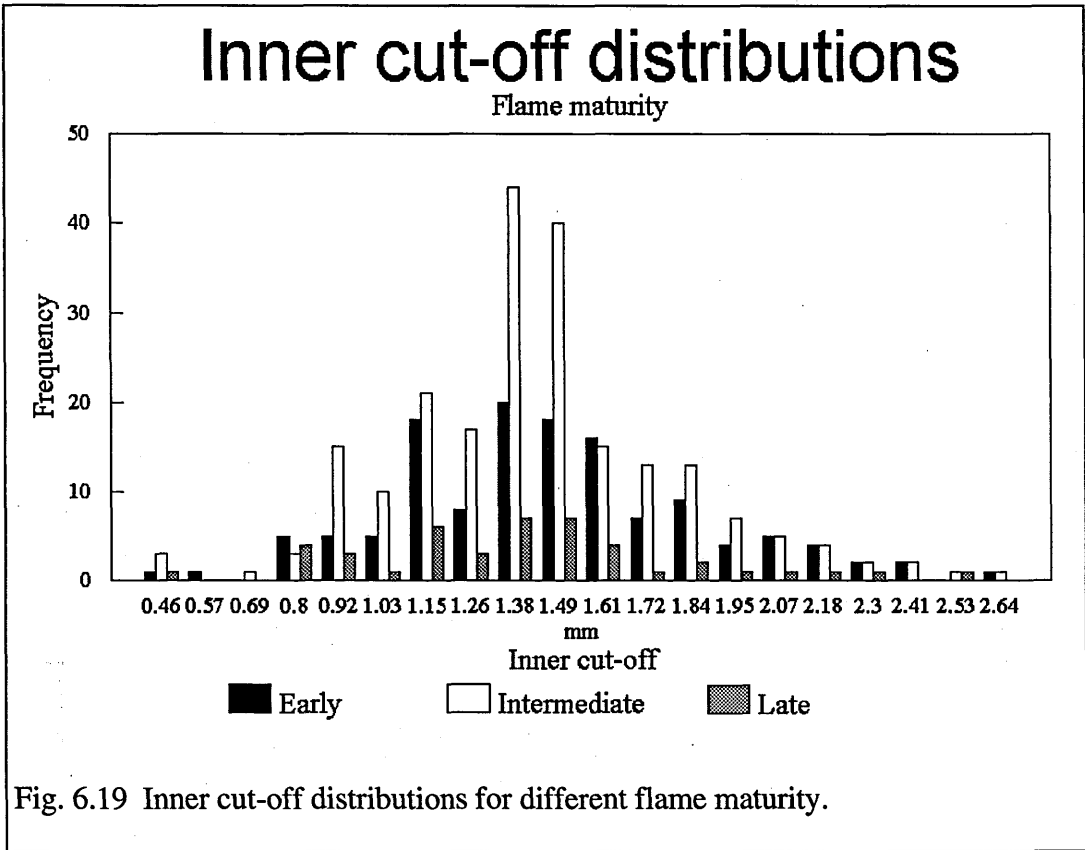
Fig. 6.18 Inner cut-off distributions for different stoichiometries.

Fig. 6.19 shows the inner cut-off distributions for the three different classes of flame maturity, with mean and r.m.s. values in Table 6.2. These distributions are consistent with those in Fig. 6.18. If there is any trend it is a very weak one toward later flames possessing smaller inner cut-offs, i.e. the smallest scale of wrinkling became smaller as the flame interacted with the turbulent flow-field. However, these

variations of mean values cannot be taken as statistically significant, as they are of order 25 % of the r.m.s.

	<u>Early</u>	<u>Intermediate</u>	<u>Late</u>
Mean	1.48	1.44	1.39
r.m.s.	0.36	0.36	0.42

Table 6.2 Mean and r.m.s. values of distributions in Fig. 6.19. Unit is mm.



It was clear from the visual inspection of the images that the flame-fronts became more wrinkled as they developed, though it was not clear whether there was a difference between the lean-limit and stoichiometric flames. The degree of wrinkling is given by the fractal dimension D . This property was measured for these experimental flames by Üngüt et. al. (1993b), who reported the distribution for the lean-limit flames as 2.23 ± 0.22 and for the stoichiometric flames as 2.25 ± 0.25 , i.e. no significant difference.

Although the degree of wrinkling increased as the flame developed into the turbulence region, the distributions in Figs. 6.18 and 6.19 imply that the scale of smallest wrinkles did not change significantly. The mean value of 1.45 mm was smaller than the apparent laminar flamelet thickness of 2.3-3.5 mm (see 6.4.1). Fractal theory assumes isotropic turbulence over all scales, whereas the turbulence field in the experiment was highly structured. This factor may have distorted the measured values of inner cut-off. The measurement of the Gibson scale and the Kolmogorov scale would have been valuable in comparing the measured inner cut-off with the different interpretations described in Section 5.2.5.3.

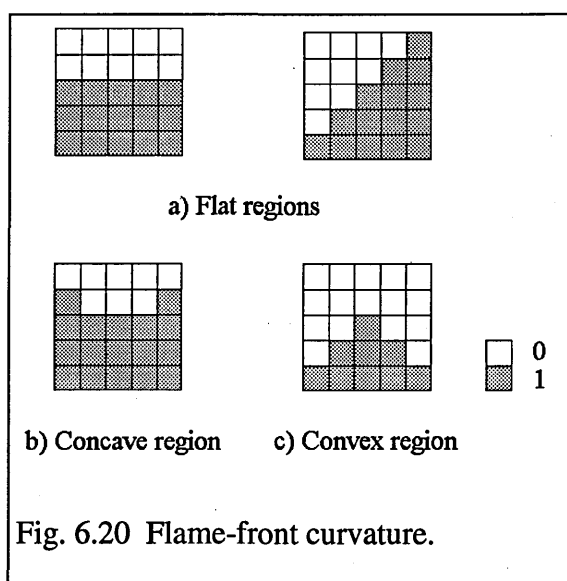
6.5.3 Local mass burning rate.

In order to investigate the apparent trend for curvature correlated variations in local reaction rate, computer algorithms that worked within the CLIPS environment were written to assign to each pixel on the flame-front values corresponding to the local flame curvature and the intensity at which the flame was burning.

6.5.3.1 Flame-front curvature.

A measure of the curvature of the flame-front at every point was required. Using the background intensity threshold value, the image was binarised, with pixels in the flame region taking the value 1 and those in the unburnt region taking the value 0. For each pixel at the boundary, the local curvature was measured.

For a flat flame-front, if a 5 x 5 pixel grid was centred on a pixel at the boundary, there would be fifteen pixels in the grid with value 1 and ten with value 0 (Fig. 6.20a). If the flame-front was concave, there would be more than fifteen pixels with value 1 (Fig. 6.20b), and if the flame-front was convex, there would be less than fifteen pixels with value 1 (Fig. 6.20c). Therefore, the number of pixels in the grid with value 1 would be a good



qualitative indication of the local curvature.

For the experimental images, the grid size was chosen to be consistent with the size of smallest wrinkles, or inner cut-off, of the flame-front, which had been measured as ~13 pixels for all images. This was the correct resolution to use for the measurements, in order to avoid discretisation errors. For a completely flat flame-front, the grid of 169 pixels would contain 91 pixels of value 1. The values for each pixel were categorised as concave, flat or convex, using the criteria in Table 6.3:

Concave	> 100 pixels
Flat	80-100 pixels
Convex	< 80 pixels

Table 6.3 : Curvature classification

6.5.3.2 Local mass burning rate.

The local burning velocity was proportional to the ratio of concentration of super-equilibrium OH to concentration of equilibrium OH (Becker et. al., 1990). If the level of equilibrium OH was assumed constant throughout a small region of an image, the local mass burning rate at each point on the flame-front would be proportional to the local maximum super-equilibrium level.

An algorithm was written to work in CLIPS that would extract the local maximum super-equilibrium fluorescence signal for each pixel on the flame-front. The logic followed closely that of Becker et. al. (1990).

The flame-front was distinguished as a steep signal gradient next to a region of signal below the background threshold. It was found by manual investigation that the reaction zone extended for typically 20-30 pixels (2.3-3.5 mm, the laminar flamelet thickness) and that the maximum flame-front signal occurred approximately 10-15 pixels from the threshold. For each pixel on the flame-front, i.e. a pixel with binarised

value unity adjacent to a pixel with value zero, the algorithm performed the following steps, illustrated in Fig. 6.21 :

- It found the normal to the flame-front,
- then searched along the normal to the flame-front in the direction of the burning region for 20 pixels,
- and registered the highest signal level.

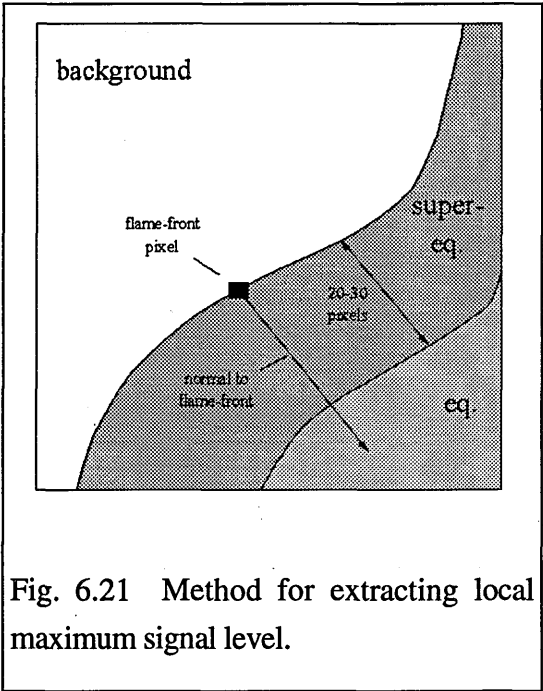


Fig. 6.21 Method for extracting local maximum signal level.

6.5.3.3 Correlation of local burning rate with local curvature.

For each PLIF image, every pixel on the flame-front was assigned a curvature class and a local mass burning rate value, which allowed a correlation map to be drawn. For each image, the distributions of maximum OH signal at the flame-front for the three different classes of curvature were plotted. Fig. 6.22 shows an example from one image.

The distribution of peak fluorescence signal for each class of curvature approximates to a wide Gaussian. It can be seen that the distribution from concave regions of the flame-front is centred at lower maximum OH intensity than the distribution for flat regions, with the convex region distribution at even higher levels. Table 6.4 shows the mean and r.m.s. values for the three distributions from this example image, where the unit is "signal counts".

	<u>Concave</u>	<u>Flat</u>	<u>Convex</u>
Mean	2696	2984	3226
r.m.s.	459	455	356

Table 6.4 Mean and r.m.s. values for distributions in Fig. 6.22. Unit is counts.

This result is consistent with the visual inspection (see 6.4.3) and implies that many convex regions of the flame-front for this image had enhanced burning rates, whilst many concave parts had suppressed burning rates.

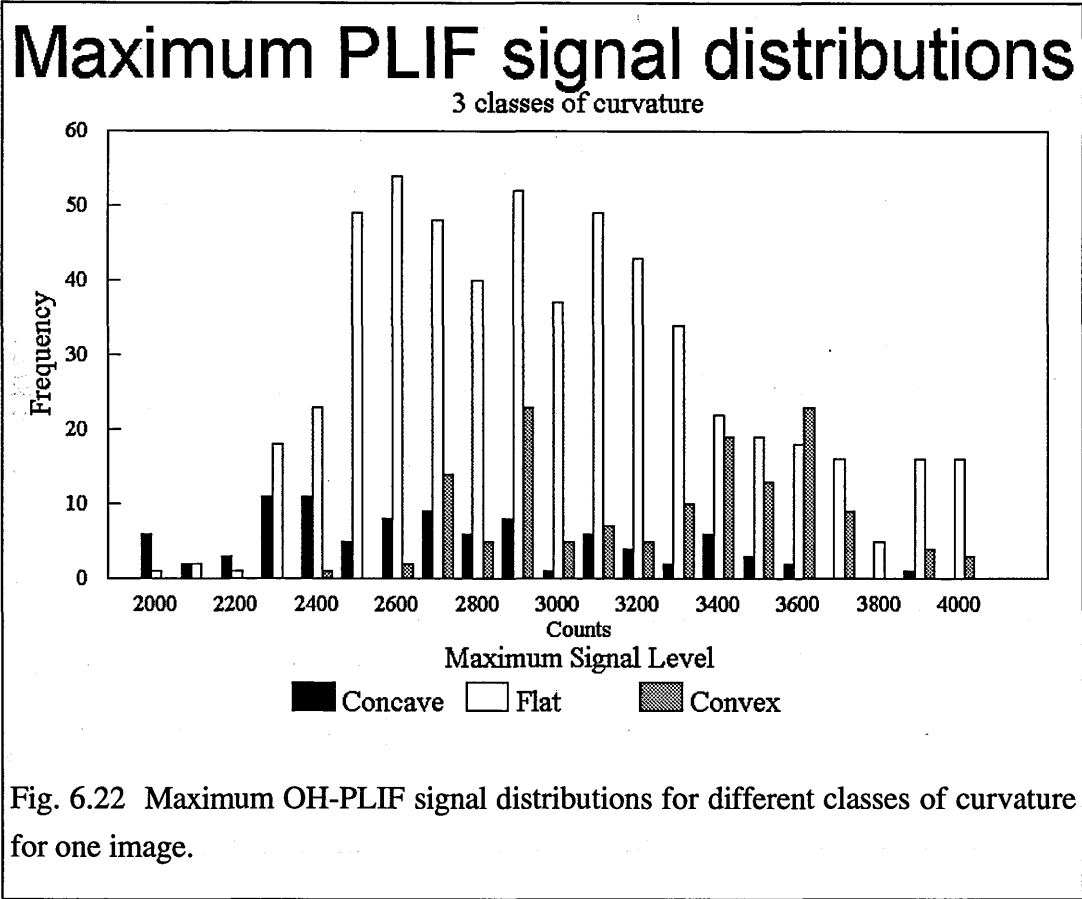


Fig. 6.22 Maximum OH-PLIF signal distributions for different classes of curvature for one image.

Fig. 6.23 shows the percentage variation of maximum OH levels for concave and convex regions of all images, split into lean and stoichiometric flames. The trend of enhanced burning rates for convex regions and suppressed rates for concave regions was seen in approximately half of the images that were analysed, whilst the other images showed no significant variation ($< 2\%$) of maximum OH intensity distribution for different curvature regimes. The mean and r.m.s. values for these distributions are given in Table 6.5, where the unit is "percentage variation of signal level".

	<u>Lean : concave</u>	<u>Lean : convex</u>	<u>Stoich. : concave</u>	<u>Stoich. : convex</u>
Mean	-2.62	+2.42	-2.59	+2.29
r.m.s.	2.73	2.34	2.48	2.59

Table 6.5 Mean and r.m.s. values for distributions in Fig. 6.23. Unit is % variation.

Burning rate variation

Lean-limit flames

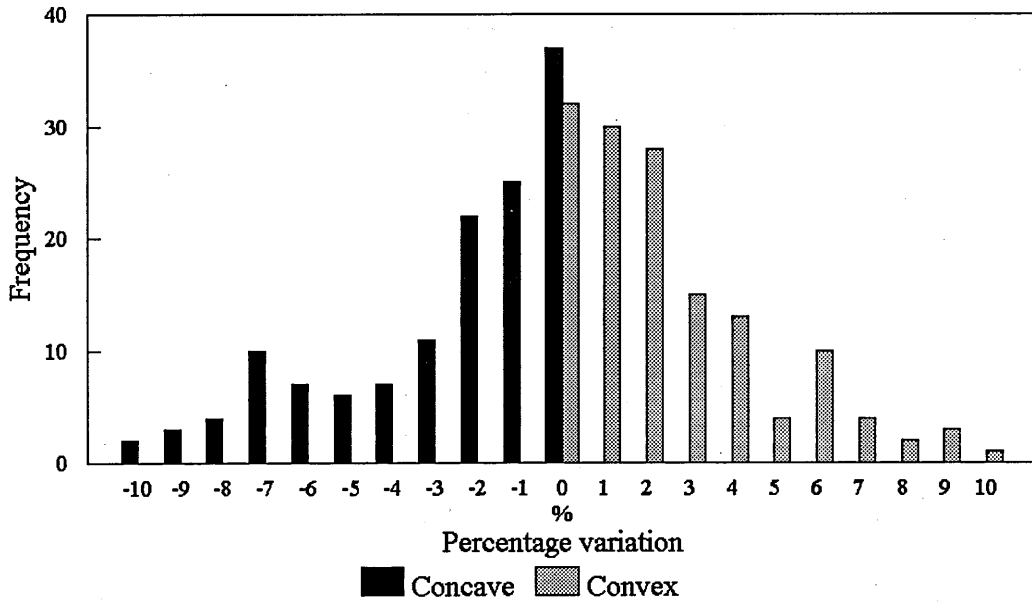


Fig. 6.23a Variation of burning rate for lean-limit flames.

Burning rate variation

Stoichiometric flames

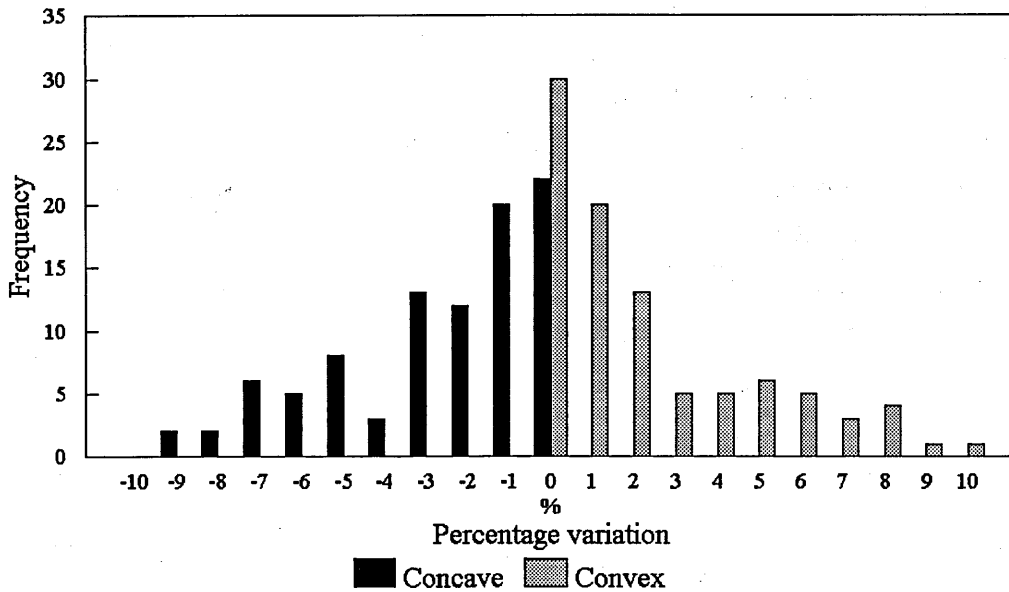


Fig. 6.23b Variation of burning rate for stoichiometric flames.

These values indicate that, although some images showed variations up to 10% of the mean signal level for flat curvatures and no images showed the opposite trend, the large number of images that displayed no significant trend caused the mean variations to be only at the 2.5 % level. The absence of a trend in some of the images might have been due to one or more of the following reasons:

1. Whilst the trend was consistent for the curvature effect of flames with Lewis number less than unity, some flames may have had a Lewis number of unity, due to different instantaneous conditions.
2. The effect of the strain rate on altering the local burning rate was not known. It may have enhanced the curvature effect in some cases and may have cancelled it in others.
3. The curvature of the flame-front out of the plane of the laser sheet was not known. For example, if the flame-front was concave in the plane of the laser sheet, burning rate suppression would be expected. However, if the flame-front had convex curvature out of the plane of the laser sheet, the effect on the local mass burning rate could have been cancelled.
4. There were variations in equilibrium OH levels and hence super-equilibrium OH levels throughout some images. This meant that the use of absolute signal levels for the local mass burning rate indicator was not always accurate, since some suppressed regions had absolute values that overlapped with other, non-suppressed regions. It would have been more appropriate, though more difficult, to measure the local ratio of maximum super-equilibrium OH level to equilibrium OH level.

6.6 Summary.

Four hundred OH-PLIF images were taken of highly turbulent premixed methane-air flames at atmospheric pressure, immediately downstream of an obstacle. The images were corrected for background noise, dark current, laser absorption and variations in laser sheet profile and pixel response. The error due to radiation trapping

was quantified as 5 %, but could not be corrected. The error due to collisional quenching variation was not measured, but reports in the literature suggested that it should not have been more than 10 %.

The images exhibited many interesting features of the effects of flame curvature and turbulence on local reaction rates. It was shown both visually and with a semi-quantitative analysis that regions of concave curvature had suppressed burning rates, while regions of convex flame curvature had enhanced burning rates. There were many examples of islands of OH, which might have been connected out of the plane of the laser sheet. There were many examples of apparently quenched parts of the flame-front, even immediately downstream of the obstacle, when the flames displayed limited wrinkling. The likelihood of quenching increased further downstream of the obstacle.

Fractal analysis of the flame-fronts produced Hausdorf diagrams similar to the theoretical form. The distributions of the inner cut-off values did not alter significantly with stoichiometry or flame maturity, with a mean value of 1.45 mm.

In order to determine whether all islands of OH were connected to the flame kernels, 3D-PLIF experiments would be required. In order to compare the effects of flame curvature and turbulence on the local mass burning rate of the flames, the strain rate at the flame-front should be measured simultaneously with the OH concentration. This aspect is investigated in Chapter 7.

Chapter 7.

Simultaneous Laser Diagnostics.

7.1 Introduction.

Previous chapters have described how OH-PLIF can provide useful instantaneous information about the variation of reaction rate in a turbulent premixed flame and the fractal nature of the flame-front. In addition, the rapidly fluctuating velocity field in the vicinity of the flame-front can be measured using Three Pulse DPIV. The combination of these two diagnostics can, in principle, provide information about the effect of turbulent strain rate on the local reaction rate at a flame-front; a subject which has received considerable interest in combustion research and could be useful in the design of combustors and the reduction of explosion hazards.

This chapter discusses the investigation of making simultaneous two-dimensional measurements of velocity and mass burning rate in a premixed flame. The background of simultaneous measurements with laser diagnostic imaging techniques is summarised. An experiment was performed to demonstrate the possibility of combining DPIV with PLIF measurements of the flame from a counterflow burner. The experimental practice is described and example images are discussed, along with suggestions for improvements of this combination of laser diagnostics.

7.2 Simultaneous Laser Diagnostics.

Instantaneous, two-dimensional laser diagnostics of many properties, such as single species concentration, temperature, velocity have been developed extensively over the last twenty years to become well established laboratory tools and even commercial systems. There are three main areas for extension, each of which has received a great deal of research interest.

- The development of reliable three-dimensional measurements, including all three spatial components of vector parameters. In addition to the fundamental preference of more complete data, by measuring a parameter throughout a volume, uncertainties experienced with 2D methods could be resolved, for example the possible existence of separated burning regions, discussed in Section 6.4.2.

- The ability to make time resolved measurements, in order to study the evolution of processes such as turbulent flows.

- The simultaneous imaging of two or more properties would allow correlations to reveal the roles of different parameters, such as the relative locations of CH and OH radicals at flame-fronts (Stårner et. al., 1992).

Each area would contribute to the general aim of obtaining more complete knowledge of processes.

7.2.1 Joint scalar imaging.

Multiple species detection using LIF was reported very early in the development of the technique. Anderson et. al. (1982) used an Argon ion laser to excite CH, CN and NCO, while Aldén et. al. (1982) used two lasers to yield linear images of both C₂ and OH. Jeffries et. al. (1986) utilised an overlap of the resonant transitions of OH, NH, CH and CN at the wavelength 312.22 nm to detect these four species simultaneously, in order to use relative concentrations of radical species to give a more useful comparison with computer models of flame-front chemistry.

Joint two dimensional imaging was performed by Namazian et. al. (1988), using a single flashlamp pumped dye laser to excite CH and simultaneously produce spontaneous Raman scattering of CH₄. Orth et. al. (1994) performed joint OH-PLIF and Rayleigh imaging to give simultaneous OH concentrations and temperature field in an SI engine simulator, while Namazian et. al. (1994) reported joint NO concentration and temperature imaging experiments in turbulent nonpremixed flames.

Simultaneous PLIF experiments have been performed by Stårner et. al. (1992), where CH and OH concentrations were measured in piloted turbulent jet diffusion flames near extinction using two lasers and two CCD cameras. Seitzman et. al. (1994) used a dye laser to produce two pulses, separated by tens of microseconds to simultaneously excite fluorescence from OH in a combusting region and acetone

seeded into the fuel. This produced two OH/acetone image pairs for investigating the evolution of large-scale structures in high-speed nonpremixed combustion flows.

7.2.2 Joint scalar-velocity imaging.

7.2.2.1 Single point measurements.

Pointwise scalar-velocity measurements are important for validating combustion models. In turbulent flows, such correlations represent turbulent transport of species, energy and other scalars (Heitor et. al., 1993). Second and third order scalar-velocity correlations appear in the averaged balance equations for enthalpy, species, momentum and turbulent stresses and many of these require model approximations, supported by experimental data.

Pointwise velocity measurements have generally been made with LDV (see 2.2.2.1). This has been combined with CARS (Goss et. al., 1988) for temperature measurements and spontaneous Raman (Dibble et. al., 1984), Rayleigh (Driscoll et. al., 1982, Driscoll and Gulati, 1988) or Mie scattering (Moss, 1980; Stårner and Bilger, 1981; Stårner, 1983; Stårner, 1986; Stårner and Bilger, 1986) for concentration measurements.

7.2.2.2 Two dimensional measurements.

Simultaneous scalar-velocity measurements in two dimensions would clearly be a natural extension of the pointwise techniques, where the velocity measurement would use the PIV technique. The ability to measure scalar-velocity correlations in 2D was of interest because it can potentially provide insight into the effect of the local velocity field, in particular the strain rate, on the flame-front characteristics of turbulent premixed flames.

The combination PIV and PLIF was reported by Simoens and Ayrault (1994). A water jet was seeded with a dye (fluorescein) in order to make concentration measurements with PLIF and with 15 μm Iridin solid particles in order to perform PIV. The experiment used the chopped output at the wavelength 488 nm from an

argon ion laser. From one laser pulse, the Mie scattered light was collected with one photographic camera, while the non-resonant fluorescence at the wavelength 515 nm was imaged onto another photographic camera. Each camera used a filter to collect from only the desired wavelength range. Fairly good agreement was reported between the classical prediction and the experimental results of the velocity-concentration correlations in this low turbulence, cold-flow application.

Frank et. al. (1996) performed simultaneous digital PLIF and DPIV on both a seeded air jet and a premixed laboratory flame. The air jet was seeded with both biacetyl and sub-micron sugar aerosols and was excited with the third harmonic of a double-pulsed Nd:YAG laser ($\lambda = 355$ nm). Fluorescence at 470 nm from the biacetyl was collected through a filter with an intensified CCD camera, while the two pulse PIV image was collected through a filter with a 2048 x 2048 CCD camera on the opposite side of the jet. These measurements of concentration-velocity correlation could give insight into the mixing structures of nonpremixed flames.

The combustion experiments used a premixed propane/biacetyl/air flame, with a flashlamp-pumped dye laser at 440 nm for the fluorescence excitation and the second harmonic of the Nd:YAG laser ($\lambda = 532$ nm) for the two pulse DPIV images. The fluorescence signal was used to binarise the measurement region at each instant into burnt and unburnt areas. The velocity fields in each region, including the velocity tangential to the flame-front were analysed. The fluorescence imaging of CH or OH radicals was recommended as providing a more accurate marker of the flame-front for studying interactions between the velocity field and the flame-front.

7.3 Experiment.

An experiment was designed to generate simultaneous vector-scalar images of the flame from a counterflow burner. Velocity measurements were made using DPIV, while scalar measurements of parent fuel fraction (PFF) and OH radical concentration in the combustion environment were made with PLIF. Essentially two parallel experiments were set-up, in that the laser-camera systems for the PLIF and DPIV were separate, except for synchronisation. The aim was to avoid interference between the two processes.

7.3.1 Application.

The experiment was performed using the Cranfield counterflow burner, described in detail by Harding (1992) and shown in Fig. 7.1. In Section 4.3.2, it was used as a flow generator in order to test the Three Pulse DPIV technique. For these measurements, the burner was run hot-flow, burning a methane-air mixture.

The application consisted of two opposing burners, separated by up to 300 mm. Each burner could be supplied with a methane-air mixture of variable stoichiometry. Balance of the two flows resulted in a flame that was stabilised between the burners.

The experimental set-up is shown in Fig. 7.2. The burner was open (i.e. there were no windows), resulting in excellent optical access for the laser sheets and cameras.

7.3.2 Laser systems.

The DPIV measurements were made using frequency-doubled Nd:YAG lasers ($\lambda = 532$ nm). In this application, a preliminary experiment showed that the typical velocities were too low for the available equipment to perform Three Pulse DPIV with the magnification factor that was used. The minimum pulse separation required for an observable seed particle displacement was of order 1 ms, whilst the maximum envelope for the generation of three laser pulses was 600 μ s (see 4.2.6). Consequently, two pulse DPIV was performed using two lasers, each run in single pulsed mode.

The PLIF measurements were made using a Lambda Physik EMG 150 XeCl excimer laser. This gas based laser could produce light in the wavelength range 307.8 to 308.5 nm, with a maximum laser energy of 150 mJ per pulse. The laser source

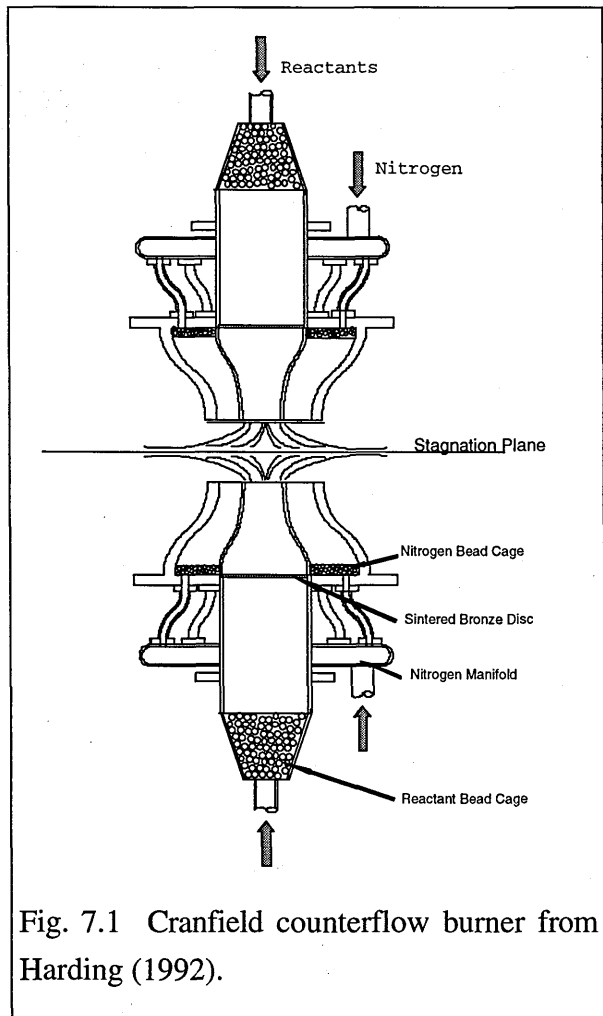
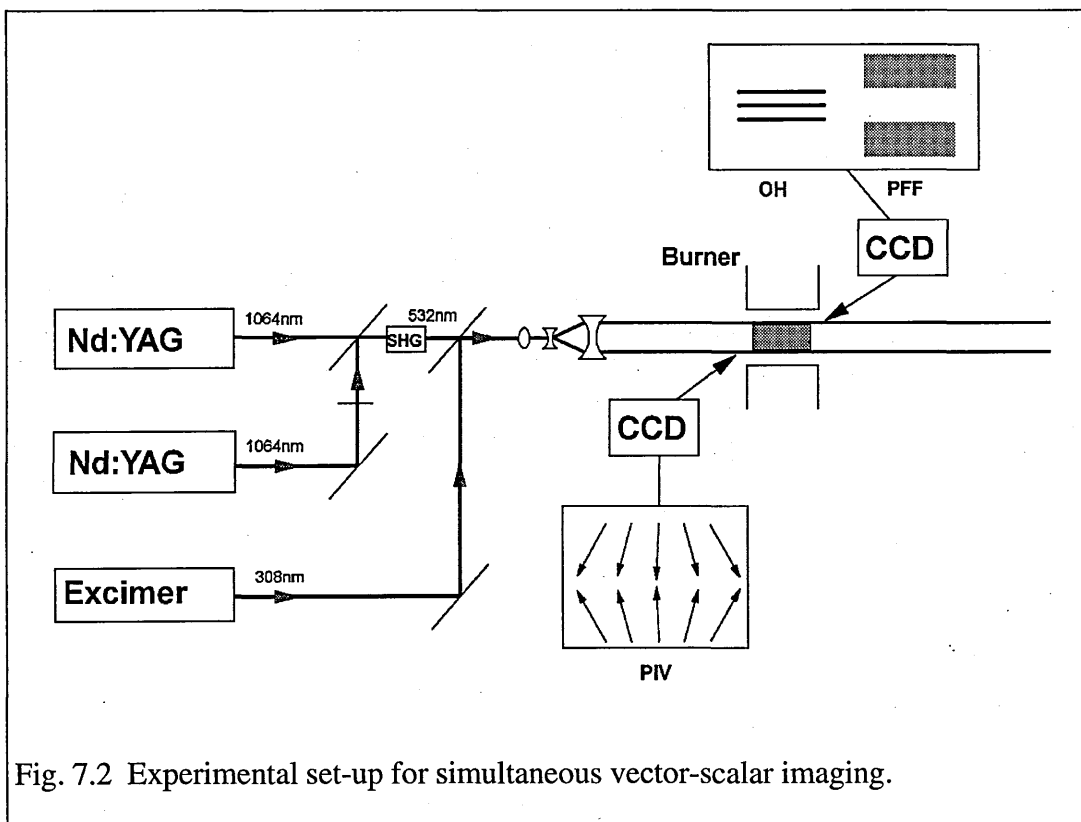


Fig. 7.1 Cranfield counterflow burner from Harding (1992).



excited the strong $Q_1(3)$ line of the ($A^2\Sigma^+ \leftarrow X^2\Pi$, $0 \rightarrow 0$ transition) of OH at 308.154 nm.

The pulse order used was :

PIV-1 (Nd:YAG 1) $\rightarrow$ PLIF (XeCl excimer) $\rightarrow$ PIV-2 (Nd:YAG 2)

The laser pulses were evenly spaced, with a pulse envelope of 1.0 ms. This combination ensured that the PLIF images were synchronous with the DPIV images.

7.3.3 Sheet formation.

With reference to Fig. 7.2, the beam from the excimer laser was formed into a sheet using a 2 m focal length spherical converging lens and a combination of a -75 mm and a +100 mm focal length cylindrical lenses, forming a Gallilean telescope. These lenses were made from silica, in order to transmit the ultra-violet light.

In order to make simultaneous measurements with the two laser diagnostics, it was crucial that the sheets were co-planar. The infra-red beams of the two Nd:YAG lasers were combined, using a half-wave plate and a polarisation mirror, before being frequency doubled to 532 nm, as described in Section 4.2.5. The green beams were

directed, via a periscope, to travel along the path of the ultra-violet laser beam, through the same sheet-forming lenses.

It was found that, due to the variation with wavelength of the optical properties of the silica lenses, the green sheet was only 15 mm in height, compared with the excimer laser sheet height and burner separation of 35 mm. In order to produce sheets of the same height, two glass cylindrical lenses (focal lengths -25 mm, +50 mm) were added after the Second Harmonic Generator and before the combining mirror, to pre-expand the green Nd:YAG laser beams.

7.3.4 Cameras and filters.

The DPIV images were collected with the large area (1340 x 1037 pixels array) Wright Instruments CCD camera, with the f/2.8, 60 mm Nikon macro lens, and the 532 nm bandpass filter, described in Sections 3.3.1 and 3.3.2. This filter excluded flame luminosity and both Mie scatter and fluorescence associated with the excimer laser pulse. (In fact, the resonant PLIF signal would not have been transmitted through the glass camera lens.)

The PLIF images were collected with the small area (600 x 400 pixels array) Wright Instruments CCD camera (see 3.3.1), with an intensifier and a silica imaging lens. Although the shutter duration was 20 ms, the intensifier gate of 50 ns prevented any Mie scattered light at $\lambda = 532$ nm from the Nd:YAG lasers from being collected with this camera.

The two cameras were placed on opposite sides of the burner and each was focused on the common plane of the laser sheets. Simultaneous calibration images of a transparent ruler permitted correlation of the measurement regions.

7.3.5 Synchronisation.

A fairly complex synchronisation circuit was required, working on the same principles as the circuits described in Sections 2.4.10 and 6.2.4, in order that three lasers, two CCD cameras and one intensifier were activated simultaneously (see Fig. 7.3). Since the flame was in a fixed position, it was not involved in the circuit (see 6.2.4).

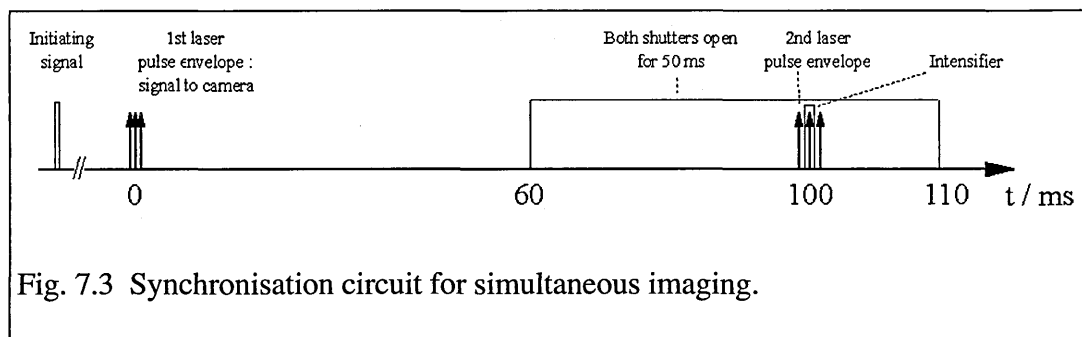


Fig. 7.3 Synchronisation circuit for simultaneous imaging.

The timing of the circuit was controlled by the Nd:YAG laser rep. rate, which was maintained at 10 Hz (see 2.4.5.4). The flashlamps and Q-switching of the two Nd:YAG lasers were controlled by the Continuum DL100 sync. unit (see 4.2.6).

When the PC controlling the PIV camera was ready and received the next flashlamp signal from the DL100 ($t = 0$), it was known that the next Nd:YAG laser pulse envelope would occur at $t = 100.0$ ms. This PC then sent a signal to the PC controlling the PLIF camera, via a delay generator, to instruct it to open the shutter. To allow time for the finite delays in the circuit, the PIV camera shutter opened at $t = 60$ ms, with a frame duration of 50 ms. The PLIF camera also opened its shutter for 50 ms. This system ensured the laser pulses would be captured, with negligible background contamination.

In parallel, a signal was sent via a delay generator to fire the excimer laser at $t = 100$ ms, with fine adjustment to place that laser pulse between the two Nd:YAG laser pulses (monitored with a fast photodiode). The excimer laser sent a trigger signal $2 \mu\text{s}$ before the pulse to the intensifier, which opened for 50 ns around the excimer laser pulse.

7.3.6 Conditions.

The upper burner was adjusted to produce a methane-air mixture of stoichiometry 1.2 (AFR 14.3, stoichiometric AFR = 17.16), while the lower burner produced a premixture of stoichiometry 0.8 (AFR 21.5). The maximum exit velocity condition of 3.5 m/s was used.

With careful adjustment, a triple flame could be produced. In this mode, illustrated in Fig. 7.4, a rich premixed flame from the premixture of the upper burner burned separately from a lean premixed flame from the lower burner premixture. Excess fuel (mainly CO and H) from the rich flame and excess oxidant (OH and O_2)

from the lean flame diffused toward the stagnation plane, where a diffusion flame was generated.

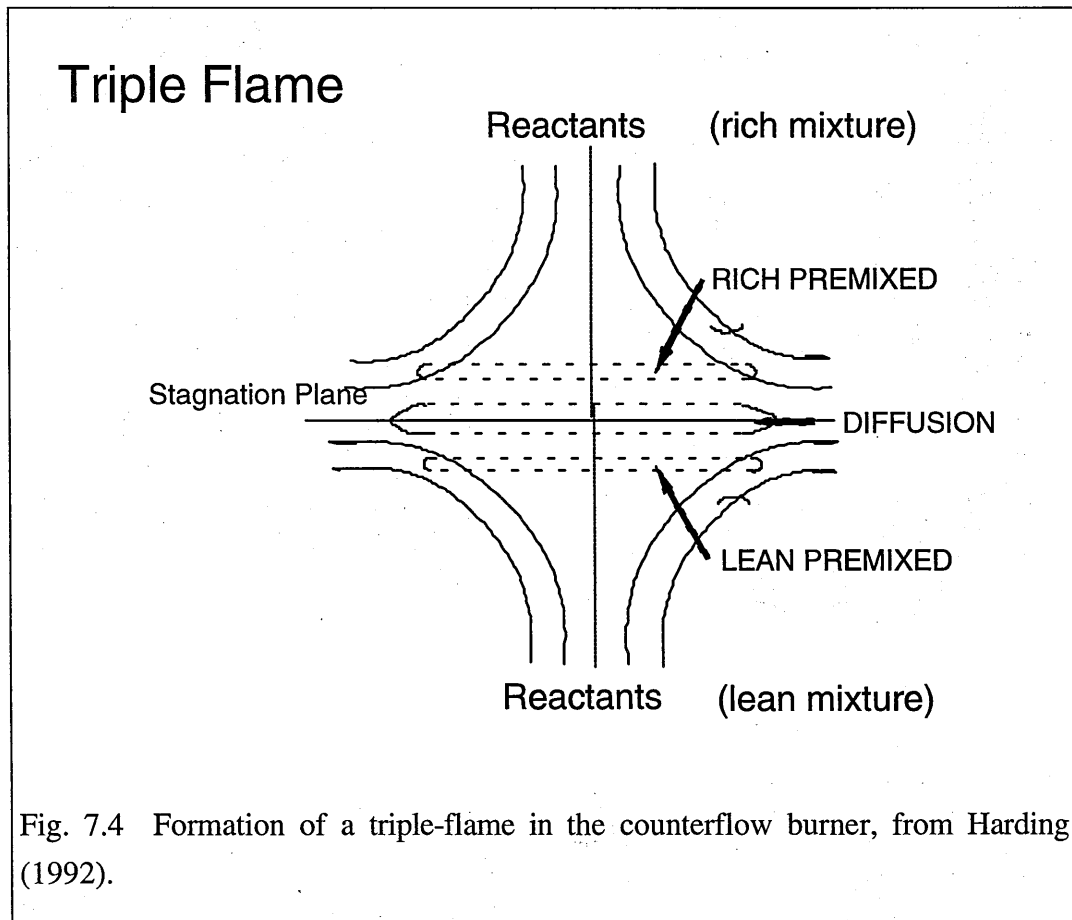


Fig. 7.4 Formation of a triple-flame in the counterflow burner, from Harding (1992).

7.3.7 Parent fuel fraction and PIV images.

The parent fuel fraction was imaged by seeding the methane supply with acetaldehyde vapour. This has been shown to be a suitable dopant for performing PLIF imaging of methane using excimer laser excitation at 308 nm (Tait, 1994).

Fig. 7.5 shows some examples of simultaneous PLIF / DPIV images, where the PLIF image of parent fuel fraction is on the left of the corresponding DPIV image. Each image shows an area of 37 x 29 mm. The PLIF images show a reasonably uniform PFF concentration in the unburnt region, which falls rapidly to zero in the burnt region. Fig. 7.6 shows the profile of Section AA' in Fig. 7.5a. The profile is flat at either side of the triple flame at a level of 1000 counts, falling to almost zero counts in the flame region.

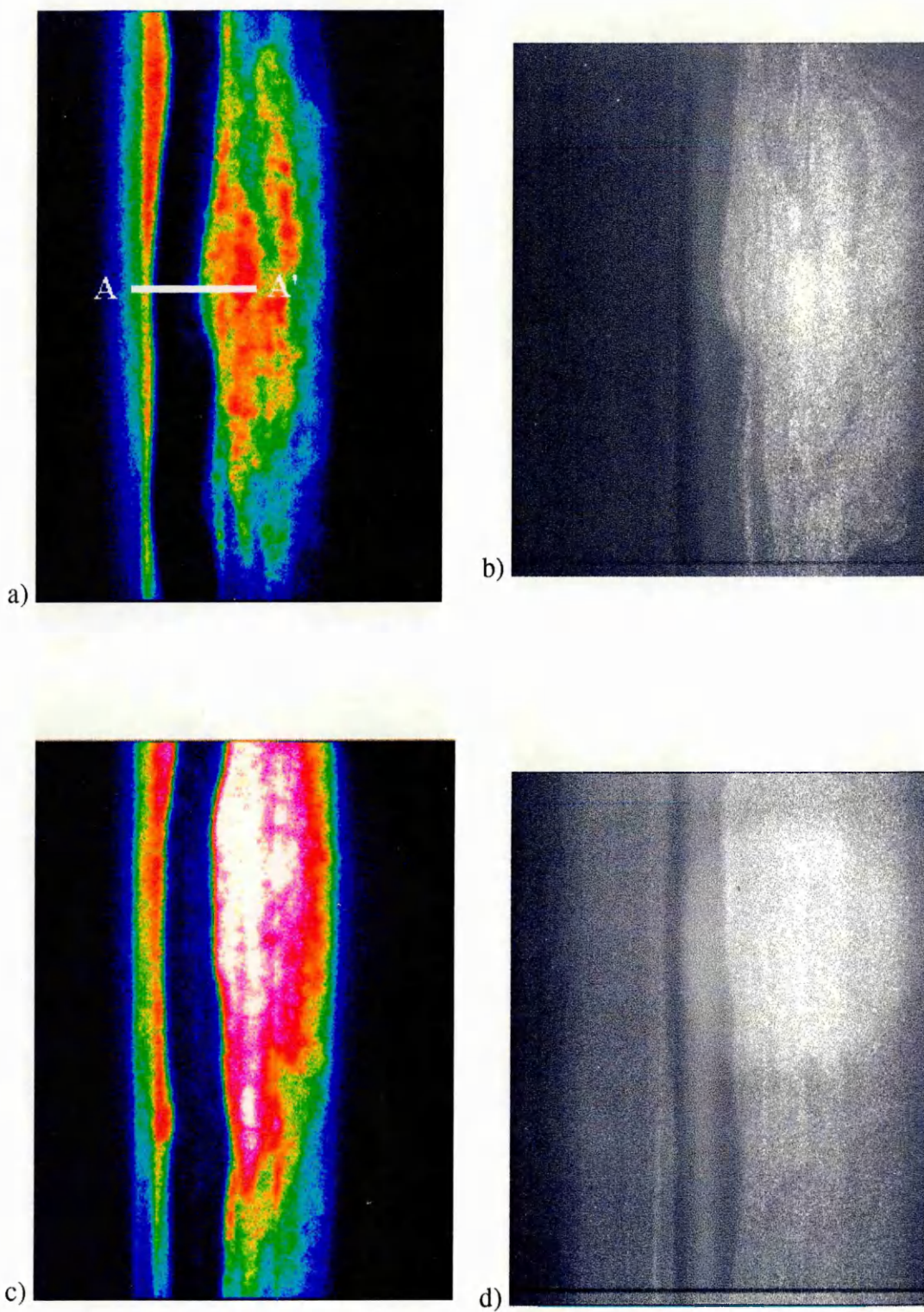


Fig. 7.5a-d Simultaneous PFF-PLIF and DPIV images of a triple flame in a counterflow burner.

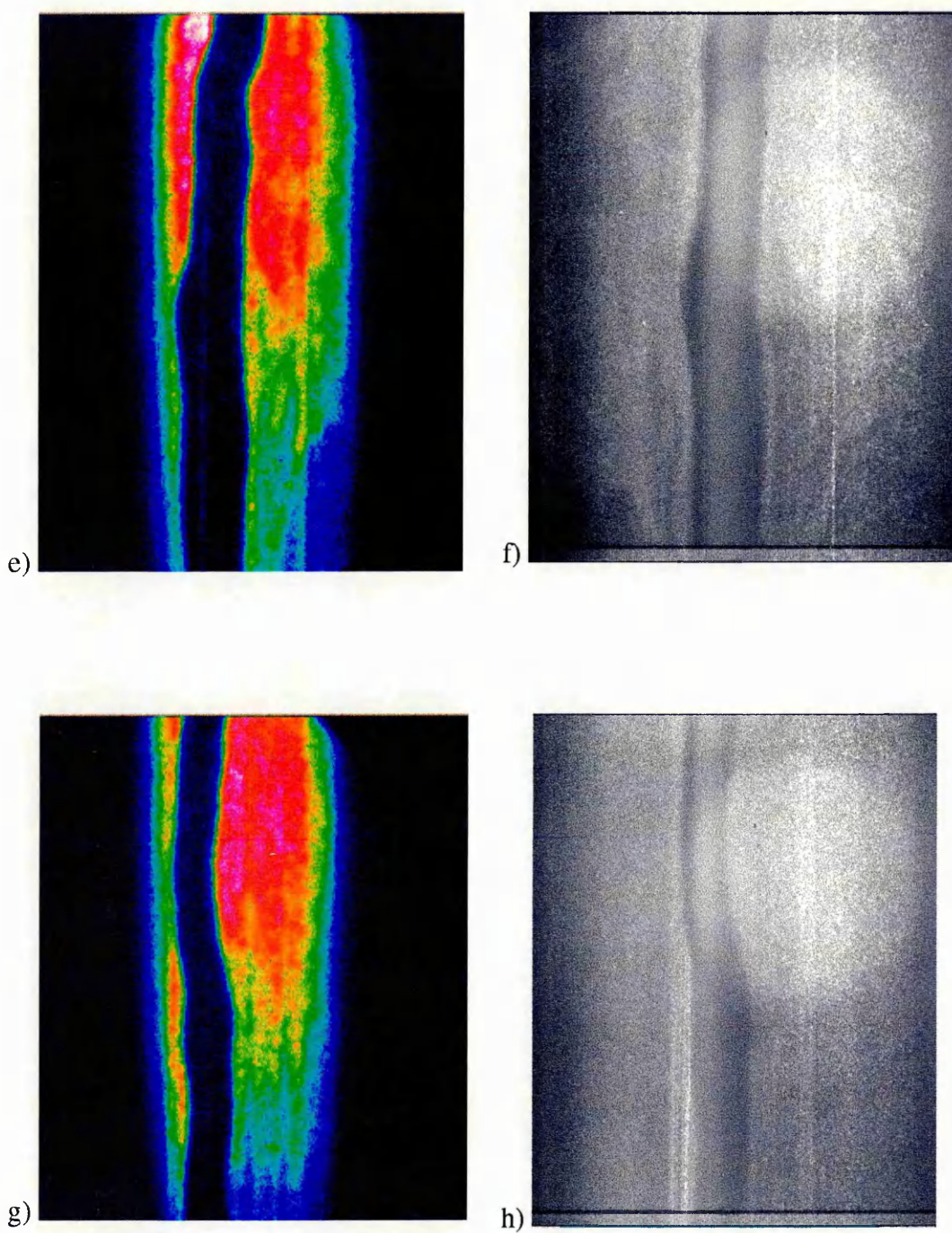


Fig. 7.5e-h Simultaneous PFF-PLIF and DPIV images of a triple flame in a counterflow burner.

The DPIV images show seed particle images in the unburnt regions, with none in the flame regions, where the TiO_2 seed particles were consumed. The concentrations and variation of seeding level prevented velocity data from being extracted, though in principle, better quality DPIV images would have provided the velocity flow-field in the unburnt region.

Comparison of the equivalent PLIF and DPIV images reveals the same flame-front geometry in each pair of images. This clearly demonstrates that simultaneous PLIF and DPIV images can be taken of a premixed combustion application.

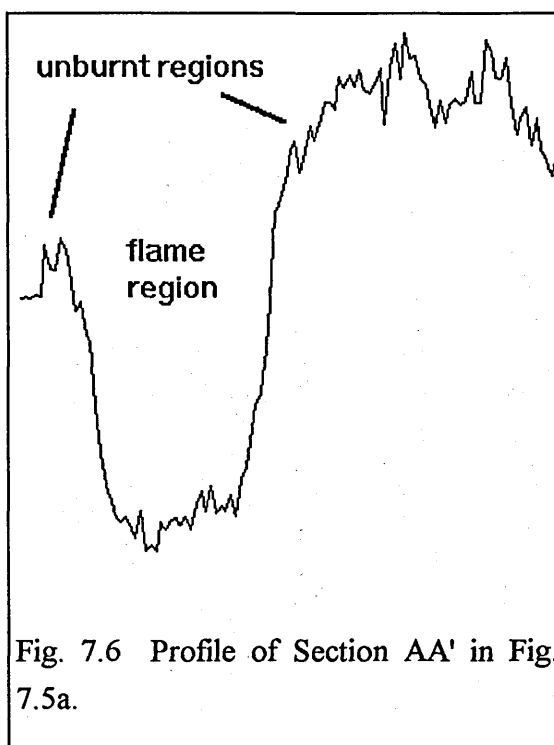


Fig. 7.6 Profile of Section AA' in Fig. 7.5a.

7.3.8 OH-PLIF images.

A series of joint OH-PLIF and DPIV images were taken of the triple flame. Fig. 7.7 shows an example pair of images. Fig. 7.8 shows the profile of Section BB' in Fig. 7.7a. The three flame regions can be clearly distinguished; a thin rich premixed flame on the left, a thin diffusion flame in the middle and a wide region of high OH on the right, corresponding to the lean premixed flame. The LIF signal had a level of approximately 250 counts.

In the unburnt region, irregularly shaped high signal regions can be seen. These signals are due to Mie scatter from the PIV seed particles at the wavelength 308 nm. These signals could not be spectrally excluded from the PLIF images, which were collected on resonance.

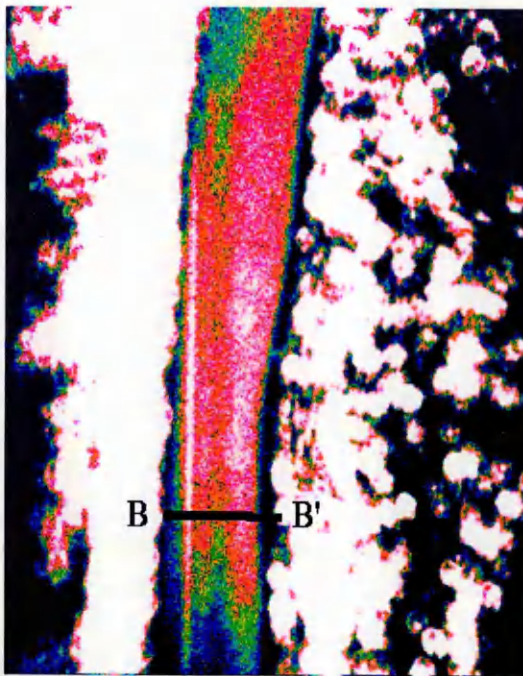


Fig. 7.7a OH-PLIF image of a triple flame.



Fig. 7.7b Simultaneous DPIV image.

The behaviour of the OH for the lean premixed flame corresponds to the images in Chapter 6; a background level in the unburnt region rising to super-equilibrium levels at the flame-front, decaying gradually to an equilibrium level in the burnt gas region. Most of the high OH region on the lean side of the triple flame shows the OH concentration decaying from super-equilibrium towards equilibrium levels.

On the rich premixed side, the OH that formed in the burnt gas due to the equilibrium water concentration and temperature (see 5.2.6) was consumed by excess CO in the hot product region ($\text{CO} + 2\text{OH} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$). This resulted in high OH signal levels occurring only at the flame-front. The diffusion flame generated an increase in OH concentration, since the OH radical is an important intermediate in the reactions occurring there.

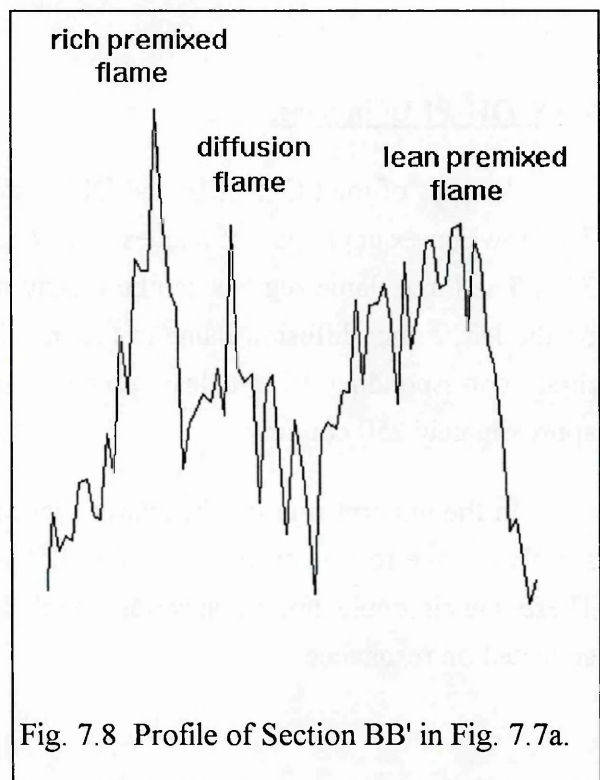


Fig. 7.8 Profile of Section BB' in Fig. 7.7a.

The DPIV images did not contain sufficiently high seeding densities to produce velocity data. Increasing the seed density caused the Mie scatter at 308 nm to swamp the resonant OH-PLIF signal, since Mie scatter is a far stronger scattering process than LIF.

7.3.9 Strategy for improved measurements.

The images obtained illustrated some interesting features, but did not provide the high quality, quantitative data that would be required for correlating flame-front effects with turbulence flow-fields in premixed flames.

The DPIV images were not susceptible to analysis due to poor seeding quality, which could in principle be improved by modifying the apparatus. The velocities of order 1 m/s were outside the capability for performing Three Pulse DPIV at the same magnification levels. Better images could have been obtained by imaging a smaller region of the flow.

The OH-PLIF images were of low signal level due to a loss of laser power, limiting the peak OH signal to approximately 250 counts. The images were contaminated with Mie scatter from seed particles. This could be eliminated by performing off-resonance OH-PLIF, for example exciting the $Q_1(5)(1,0)$ line at 282 nm with a pulsed dye laser and collecting fluorescence from the strong (1,1) band near 315 nm (Seitzman and Hanson, 1992). Modern lasers would be able to produce higher pulse energies, resulting in a better signal to noise ratio.

7.4 Summary.

An experimental combination of the two laser diagnostics PLIF and DPIV was performed on a counterflow burner. Joint PFF-velocity images demonstrated that simultaneous images of the application could be obtained. OH-PLIF images showed the structure of the triple flame, but were contaminated by ultra-violet Mie scatter from seed particles. To perform joint OH-PLIF - DPIV imaging effectively, off-resonant LIF must be performed.

In both sets of images, the seeding density and non-uniformity made it impossible to extract velocity information from the DPIV images. However, this was a feature of the experimental conditions and could be overcome in principle.

Chapter 8.

Summary and discussion.

This project investigated the possibility of combining two laser diagnostic techniques, PIV and LIF, applied to turbulent premixed flames, where the interaction of the turbulent flow-field with the rate of reaction has been of considerable interest in the field of combustion research.

PIV has been established as the best available method for making two-dimensional velocity measurements. The use of a digital camera for the image collection brings many advantages and was used exclusively for this work. The standard two pulse monochromatic technique was explored. A Monte-Carlo simulation suggested optimum values of seeding density, interrogation region size and the maximum velocity variation within an interrogation region; these were in broad agreement with the results of previous work.

The simulations led to the conclusion that for relatively small CCD array sizes (600 x 400 pixels), the ability to closely tailor the interrogation region size to the images was important. The use of FFT algorithms was restrictive in this regard, so an analysis program was written to incorporate a direct numerical calculation of the autocorrelation function.

Two pulse DPIV was applied to uniform flows, producing velocity vector maps of a high standard. When applied to non-uniform flows, the two principal drawbacks of two pulse monochromatic PIV were illustrated; an inability to resolve the sign of the flow direction and increased vector drop-out due to a lower signal to noise ratio in the autocorrelation function.

Turbulent flow-fields, with fluctuating velocities, require a technique that can provide directionally resolved velocity measurements. Various different approaches that have been reported were discussed in Chapter 2. Most involve extra experimental equipment, can be complex to perform, and can introduce uncertainties into the results.

The use of multiple monochromatic pulses imaged within a single exposure was investigated. The addition of a third, unequally spaced laser pulse coded the flow

direction for a triplet of seed particles images to be from the shorter to the longer displacement. The only modification to the experimental set-up required was the incorporation of an additional Nd:YAG laser and a synchronisation unit.

A triple-correlation function was used to directly extract the directionally resolved velocity information from the Three Pulse DPIV images. Essentially, it correlated triplets of seed particle images with the correct relative displacements. The stricter criteria of the triple-correlation function reduced the probability of noise correlations, resulting in less vector drop-out.

A complete DPIV analysis system was written to run on both UNIX workstations and DOS/Windows PCs. This could perform either two pulse autocorrelations or three pulse triple-correlations on each interrogation region, depending on the variation of DPIV that was used. The analysis included binarisation, centroiding of the correlation function and a post-processing routine that performed a continuity check between adjacent vectors. If a vector was rejected, it could be replaced with an alternative candidate from the same correlation function, or an interpolated vector.

The Three Pulse DPIV technique was successfully applied to a number of cold flows, such as turbulence at the edge of a nozzle flow and the flow from a counterflow burner, which provided extreme flow reversal.

In order to measure the mass burning rate of premixed flames over a two-dimensional area, PLIF of the OH radical has become the best available and most widely used method. OH-PLIF measurements were made of a rapidly expanding premixed methane-air flame at atmospheric pressure in a wind tunnel that provided excellent optical access.

More than four hundred experimental images were corrected for systematic errors due to dark current, background signal, variations in laser sheet intensity and pixel response and signal loss due to laser absorption. Estimates of the errors due to radiation trapping and quenching variation were made.

Qualitative analysis of the images showed that the expected regimes of OH concentration were clearly visible; background levels in the unburnt gas, equilibrium levels in the burnt gas and super-equilibrium levels in the vicinity of the flame-front. The images exhibited interesting features, such as islands of signal, possibly due to fingers of flame, connected out of the plane of the laser sheet. Regions of the flame-front with convex curvature appeared to have higher OH signal levels, indicating enhanced burning

rates, whilst regions with concave curvature appeared to have suppressed burning rates. Some regions, particularly in the more developed flames, appeared to be quenched.

Fractal analysis of the flame-fronts measured the inner cut-offs; the smallest scale of wrinkling. The distribution gave a mean value of 1.45 mm for the inner cut-off. This value did not appear to vary with stoichiometry. A weak trend with maturity of flame could not be regarded as statistically significant.

Quantitative correlation of the local maximum fluorescence level with the class of curvature revealed that up to 50 % of images did not display a significant variation of reaction rate with curvature. Those images that did show a reaction rate variation showed a clear trend for convex parts of the flame-front to have enhanced reaction rates, with concave regions having suppressed reaction rates. These trends appeared for both lean-limit and stoichiometric flames and were consistent with premixed flames with Lewis number less than unity. However, the strain rate acting on the flame-front due to the turbulent flow-field could not be extracted from OH-PLIF images alone.

These DPIV and PLIF experiments established that simultaneous OH-PLIF and DPIV measurements of a turbulent premixed flame should provide information about the effect of the turbulent flow-field on the reaction rate and this could be compared with curvature effects. In order to demonstrate the feasibility of making such measurements, a simultaneous imaging experiment was conducted on a counterflow burner triple flame.

Joint parent fuel fraction PLIF - DPIV images clearly showed that simultaneous images of the flame could be made. the PFF images showed high levels of premixture in the unburnt regions, falling to zero levels in the flame region.

Joint OH-PLIF - DPIV images were generated from the triple flame. The PLIF images showed the three flames, but were contaminated with Mie scatter from the seed particles.

The DPIV images could not provide velocity information due to incorrect seeding levels, though in principle this would have been possible.

In order to generate high quality joint OH-PLIF - DPIV measurements, it would be essential to perform off-resonant fluorescence, in order to remove competing laser generated signals. As laser pulse energies increase, a variety of excitation and collection strategies are likely to be available. It is likely that PIV will increasingly be performed digitally, as the array sizes increase towards the spatial resolution of photographic film.

CCD cameras that can generate images of resolution 1024 x 1024 pixels, separated by 1-5 μ s are becoming commercially available. These cameras will allow two pulse, two frame, monochromatic DPIV to be performed, using cross-correlation analysis to extract the flow direction directly.

Simultaneous imaging of velocity and species concentration in two dimensions have become possible with current technology. The ability to measure the temperature in a premixed flame over a two-dimensional region, with an accuracy of ± 10 K, would enhance turbulent combustion research. Ultimately, the aim should be the collection of three-dimensional temperature, species and velocity data, at rates that would allow tracking of the turbulence - combustion interaction.

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