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Journal

Measurement Science and Technology, 11(7)

ISSN

0957-0233

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Publication Date

2000

DOI

10.1088/0957-0233/11/7/304

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Measurement of fuel mixing and transport processes in gas turbine combustion

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Received 28 January 2000, in final form 30 March 2000, accepted for publication 13 April 2000

Abstract. The measurement techniques for delineating fuel–air mixing and transport in gas turbine combustion, as well as examples of representative results, are provided in this overview. The summary is broken into applications for gaseous fuels and liquid fuels since many diagnostics which are specific to the phase of the fuel have been developed. Many possible methods for assessing the general mixing have been developed, but not all have been applied to practical systems either under scaled or under actual conditions. With respect to gaseous mixing processes, planar laser-induced fluorescence (PLIF) based on acetone is now starting to be successfully applied to actual systems and conditions. In spray-fired systems, the need to discriminate between phases leads to considerable complication in delineating fuel–air mixing. Methods that focus on the discrete phase have successfully provided details relative to the droplets. These include phase Doppler interferometry (PDI), which is becoming ubiquitous in application to practical devices and under practical conditions. PDI is typically being applied to quantify droplet sizes, although the volume flux, which is relevant to fuel–air mixing, in practical systems is also being reported. In addition, PLIF strategies that focus upon the behaviour of the droplets are now being developed. However, PLIF strategies that can discriminate between phases either in the fuel or with respect to the liquid fuel and combustion air are also being developed. In terms of characterizing the vector fields associated with the mixing process, laser anemometry (LA), although it is tedious to apply, has proven reliable even in the presence of droplets. Newer methods such as DPIV and FRS have seen only limited application in practical systems but appear promising. In terms of scalar fields, LIF and PLIF have also been applied successfully to these systems, and examples of the measurements of concentrations of various radical species such as OH are found throughout the literature.

Keywords: fuel–air mixing, aerodynamic flowfield, velocity, concentration, laser-induced fluorescence, flame ionization detector, CCD camera, photomultiplier tube, imaging, sample probe, particle image velocimetry, planar laser-induced fluorescence, gas turbine combustion, combustion diagnostics, spray combustion, natural gas combustion

1. Introduction

The motivation for understanding the dynamic and coupled phenomena associated with gas turbine combustion is driven by a need to improve the overall operability of combustion devices while reducing the amount of pollutants produced and improving efficiency. The complex nature of gas turbine combustion is associated with the large number of processes occurring. See, for example, figure 1 for a typical swirl-stabilized reaction occurring within the combustor.

Gas turbine combustion is utilized today to provide both ground-based power generation and propulsion for aero applications. In the case of power generation, gas turbines are fuelled either with gaseous fuel or with liquid fuels. In the cases in which control of emissions is of great concern, gaseous fuels are required and natural gas is typically utilized.

However, in cases in which economic requirements lead to the use of liquid fuels, a fuel that is readily available and relatively inexpensive is utilized. In this case common fuels such as diesel and naphtha are used. For ground-based systems, improvements in efficiency translate directly into cost savings as well as a reduction in emission of CO₂, which has implications relative to global warming.

For practical reasons, aero engines rely exclusively upon liquid fuels. Because of safety concerns the specifications of these fuels are well documented. In commercial engines, Jet-A is utilized throughout the world, whereas JP-8 is the current fuel of choice for military applications. Because the fuel type is fixed, the requirements for the combustion system do not vary as much as they do for ground-based systems. From a safety standpoint, the failure of aero engines cannot be tolerated. Hence, the maintainability and durability of aero

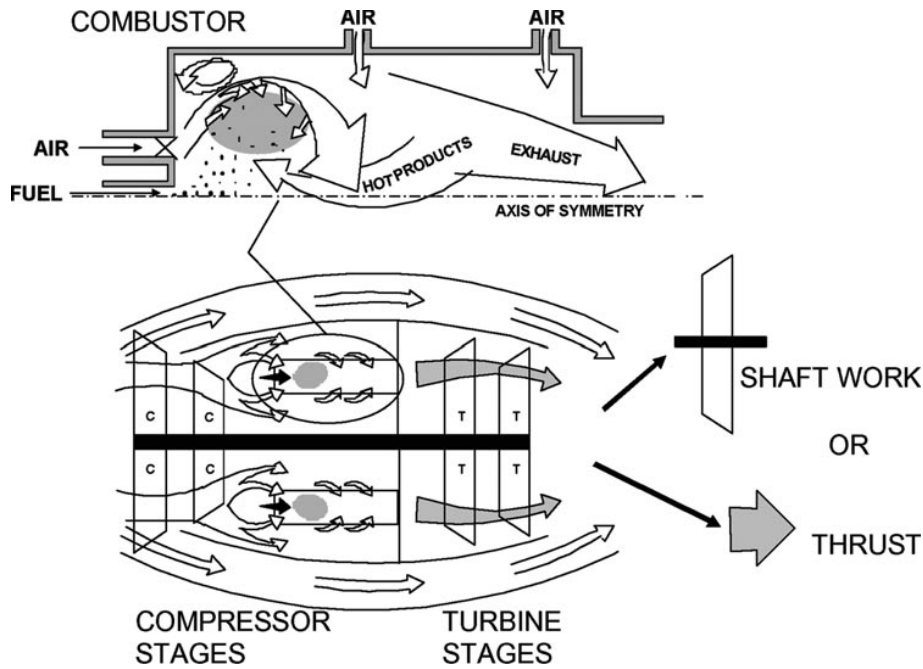


Figure 1. Basic processes in a simple cycle gas turbine engine and associated phenomena occurring within the combustor.

engines is a critical issue, together with factors concerning emissions and fuel economy. Fuel economy translates into savings in the cost of the fuel as well as into the reduction in the emission of CO_2 . The increasing prevalence of taxation associated with emissions also drives the economic considerations related to performance regarding emissions and fuel economy.

Both for gas-fired and for liquid-fired gas turbines, the performance of the combustor is perhaps the most critical aspect of the engine. The method of combustion dictates the amount of pollutants formed and ultimately emitted by the engine. The combustion system is subject to thermal strain due to temperature gradients and heat transfer issues. As a result, it can be a limiting factor in terms of the durability and reliability of these devices. In addition, the combustion system dictates the temperature profile of the gases entering the turbine. Hot streaks and changes in temperature profile associated with degraded combustion performance and/or components can affect turbine components and the reliability and durability of these parts. In each of these cases, the fuel injection and mixing behaviour are key factors determining performance.

As designers struggle to reduce emissions and improve efficiency while at the same time increasing reliability and durability, understanding the basic processes occurring within the combustion system becomes increasingly important. This is in part due to the cost of design, but also to the improvements that have already been made in combustion system design over the past 25 years. Eking out additional improvements without contributing to the exorbitant cost associated with employing trial and error strategies requires experience coupled with a detailed understanding of the basic processes. The use of constantly evolving numerical and experimental tools to provide the necessary insight is promising. Recent advances that have been made in

the development of experimental tools have resulted in additional insight into the basic physics occurring in complex combustion systems. In some cases, non-reacting flowfields are interrogated in addition to reacting cases in an effort to reduce the complexity of interpreting the combustor flowfield. Such measurements are required in order to detail the physics of the phenomena occurring as well as to validate models proposed for comprehensive numerical predictions.

To organize the paper, the fuel injection and transport measurement issues in gas turbine combustion are divided into three elements: (i) injection and mixing of gaseous fuels, (ii) injection and mixing of liquid fuels and (iii) transport and combustion. The synergism amongst these elements cannot be overlooked. For example, in the continuous combustion process, the transport of the ignited mixture promotes vaporization that in turn affects the unmixedness. A synergism amongst the elements also produces fundamental boundaries such as 'lean and rich extinction limits'. In addition to examining each element, the interaction amongst the various elements is presented. Hence, the purpose of this paper is to present an overview of the current measurement strategies that are used to elucidate details of the fuel injection and transport phenomena in gas turbine combustors, such as that shown in figure 1. Examples of these measurement techniques are provided and specific references that provide additional detail regarding the methods are cited.

2. Fuel injection and mixing

Perhaps the most critical aspect of the combustion process is the introduction of fuel into the device and its subsequent mixing with air in the device. In this section, a distinction between gaseous and liquid fuels is made since many of the measurement methodologies and strategies differ according to the phase of the fuel. In the case of liquid fuels, additional

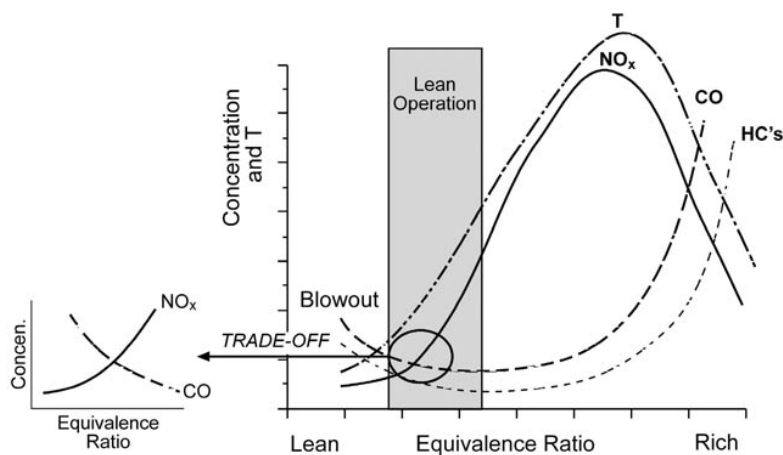


Figure 2. The trade-off of stability and pollutant emissions.

steps of atomization and vaporization are required prior to mixing. The presence of the discrete phase thus requires the additional understanding of transport-related processes.

Various methods are utilized to mix the fuel and air depending upon the application. In advanced combustion concepts, careful premixing of the fuel and air prior to combustion is required in order to ensure that homogeneous reaction temperatures are obtained. This is true both for catalytic and for non-catalytic combustion strategies. In non-catalytic applications, the goal is to reduce local peak temperatures in the reaction zone, thereby reducing the formation of thermal NO_x. However, with 'perfect mixing' comes a decrease in stability, which can lead to constraints relative to operability. Figure 2 illustrates the typical trade-off amongst production of NO_x, production of CO and stability for non-catalytic systems.

As a result of the trade-off between stability and emissions, optimum performance will be attained not with ideal mixing, but rather with an intelligent strategy of fuel placement and mixing. As a result, the characterization of the local fuel-air ratio upstream of the reaction and the relationship of the fuel-air ratio to the combustion performance are of great interest.

The mixing of the fuel prior to its entry into the reaction region is also crucial for achieving high performance in catalytic systems. Having a homogeneous fuel-air mixture in these cases is important for maintaining a uniform temperature throughout the catalyst bed and preventing overheating the reactor, which can occur in cases with locally rich pockets of fuel.

In this section, examples both for gaseous and for liquid fuel injection scenarios will be provided.

2.1. Gaseous fuels

Gaseous fuels are utilized in gas turbines for stationary power generation for industry, utilities and independent power producers. Natural gas is the most commonly used gaseous fuel, although the inherent robustness of the gas turbine allows consideration of other gaseous fuels including those obtained from biomass and other renewable sources. Owing to the differing heat content and ignition delay properties of

these fuels, the fuel injection and mixing techniques must be tailored to some extent on the fuel composition. The varying properties associated with these fuels also highlight the need to understand fuel preparation and mixing processes. Methods that provide a direct measure of the local fuel-air ratio are desired. It is also desired to characterize the behaviours of actual fuels rather than simulants since scaling is difficult to establish. Various measurement techniques can be utilized to characterize the local fuel-air ratio both in a steady state and in a time-dependent manner. Some of these methods are non-intrusive, whereas others are intrusive. The following discussion is divided into 'tracer-based' and 'non-tracer based' methods that are either intrusive or non-intrusive.

2.1.1. Intrusive non-tracer based methods. In intrusive, non-tracer-based methods, the descriptor implies that the fuel is not altered, doped with or replaced by a simulant that has desirable measurement or operational characteristics. In other words, the combustion system is operated exactly as it would be, with the gaseous fuels that are used in practice. The intrusive descriptor implies that a physical device must be inserted into the flowfield. These non-tracer-based methods require that a method for directly measuring the concentration of natural gas (or some other gaseous fuel) be available.

Measurements with intrusive probes have been made in reacting and non-reacting systems for many years. As a result, several excellent reviews of various applications in homogeneous combustion are available in the literature (Bowman 1977, Bilger 1977). Although much attention and effort has been devoted to the accurate measurement of gaseous products of combustion by intrusive probes (Nguyen *et al* 1995, Zabielski *et al* 1981, Samuelsen and Benson 1977), extractive sampling through these probes can be used to obtain information related to the mixing of gaseous fuels prior to combustion. For example, it might be desirable to assess the local fuel-air ratio both under reacting and under non-reacting conditions in order to assess fuel-air mixing. In advanced engines (e.g. dry low NO_x, catalytic), preparation of the fuel-air mixture prior to combustion is crucial for its performance. A small probe can be inserted into the flowfield, extract a sample of the gas and convey it to an analyser

which can then determine the relative amount of fuel at a given position in the flow. This can be accomplished using any fuel that can be measured by standard detectors (e.g. a flame ionization detector) and in a high temperature, elevated pressure environment.

In a flowfield without recirculation, it is possible to sample in an 'iso-kinetic' manner to help reduce probe perturbation effects. By sampling iso-kinetically, the probe opening brings in a mass flow of material that would have been contained in the volume occupied by the physical probe, thus minimizing the distortion of the streamlines in the vicinity of the probe. This may be possible in well-behaved flows that might exist within a premixing duct, for example. However, in the complex elliptical flow that is typical of gas turbine domes, it is difficult to avoid perturbing the flow†. For many complex systems, however, an extractive probe measurement can provide useful information. Purists may prefer to utilize non-intrusive methods if possible (as discussed in section 2.1.2), but limited optical access and uncertainties in the skill of operators performing the measurements often limit the application of non-intrusive methods.

Figure 3 shows an example of a fuel injection system set-up and an associated measurement of fuel concentration within the measurement plane. In this study, the injector hardware can be configured to inject from the locations shown by the bent arrows in figure 3 (either wall jet or centrebody). The results shown in figure 3 demonstrate the type of information that can be obtained by extractive probe measurements. The results shown in figure 3(b) were obtained using a grid of 90 points distributed throughout the measurement plane of interest, which was, in this case, at a location 3 mm downstream of the centrebody face. Because recirculation occurs, the sampling is not iso-kinetic.

In this particular case, the combustion performance was found to be a function of the proportions of the injection split between the two circuits, one injecting radially outwards from six centrebody jets (% CB) and one injecting radially inwards from six wall jets (% WJ). Figure 4 illustrates the difference between the fuel distributions observed for injection from the centrebody and from the wall. In this case, a well-mixed fuel distribution was obtained with the 50% CB condition (see figure 4(b)). As more fuel is injected from the centrebody, higher concentrations of fuel appear near the centreline. The asymmetry noted in the plots can be attributed to the relative alignment of the fuel jets (six in total) and the swirler vanes (four in total). As a result, the orientation between the fuel distribution and swirler vanes cycles every 180° with respect to the centre. The results in figure 4 reflect this characteristic with symmetrical behaviour observed across the halves of the flowfield. As a result, despite the intrusive nature, useful information can be obtained in a relatively quick fashion. Although this information is obtained using intrusive methods, the results provide insight into the details of the fuel distribution as a function of the injector operation.

† 'In mathematically elliptic flows, such as recirculation regions, disturbances from the probe always will propagate upstream. Although the problem is obvious, it does not appear to have been addressed in the literature, not even to the extent of saying that visual observations indicated no effect! Of course up to now we have been pleased to have any sort of measurements in such regions.' (Bilger 1977).

It is also possible to utilize intrusive probes to provide time varying information relative to the gas concentration. One strategy involves absorption of energy by the fuel. The Lambert-Beer law describes this absorption theoretically:

$$\frac{I}{I_0} = e^{-\alpha CL} \quad (1)$$

where I is the intensity of energy after passing through an absorbing media, I_0 is the intensity of energy prior to passing through the medium, α is the absorption coefficient of the medium, C is the concentration of the medium and L is the pathlength.

For hydrocarbons, a strong absorption band is present at wavelengths of 3.3–3.5 μm . Fortunately, relatively inexpensive lasers that operate at a wavelength of 3.39 μm are available. Since most hydrocarbons absorb energy at this wavelength, to determine the concentration of a specific gas (or blend of individual gases, such as natural gas), a calibration procedure must be conducted in order to isolate the absorption coefficient. The absorption coefficient of the hydrocarbon gas(es) of interest can be determined by a procedure that involves flowing specified concentrations through a cell with a known pathlength, and monitoring the attenuation of light passing through the cell as a function of concentration. As a result, by passing a 3.39 μm wavelength laser beam through the flowfield containing gas and measuring the attenuation, the concentration of hydrocarbon fuel within the beam pathlength can be determined. This strategy has been further refined spatially by using an intrusive probe with a relatively short pathlength (Mongia *et al* 1996). The accuracy of this measurement depends upon having accurate knowledge of the pathlength and the absorption coefficient. The pathlength is established by knowing the distance between the windows. However, the absorption coefficient, which depends on the ambient temperature as well as the molecular structure, must be determined by calibration. As a result, in a flow with temperature gradients (e.g. with elevated inlet temperatures), the uncertainty in the absorption coefficient may be significant, depending upon the fuel utilized. The frequency response of this system is limited only by the electronics and therefore can be utilized to evaluate high frequency fluctuations in concentration. Extracting a sample and running it through a cell through which the 3.39 μm laser beam is passed can render this system more rugged. If the overall volume of the sampling system can be made small enough, a reasonable level of frequency response can be achieved (e.g. approaching 1 kHz).

Hot-film strategies can also be used in conjunction with intrusive probes. Intrusive probes that implement hot-film methods include a probe manufactured by TSI (Model 1440) that utilizes a constant temperature anemometer to maintain the temperature of a hot film. In such a device, the heat transfer between a thermal sensor and the environment is measured. This heat transfer depends on the temperature, static pressure, velocity and thermal properties of the gas. A sonic orifice can be utilized to ensure that the velocity is constant. In this case, as long as the temperature is accounted for (or is constant), the probe measures the ratio of the specific heats of two gases. Hence, the hot-film probe

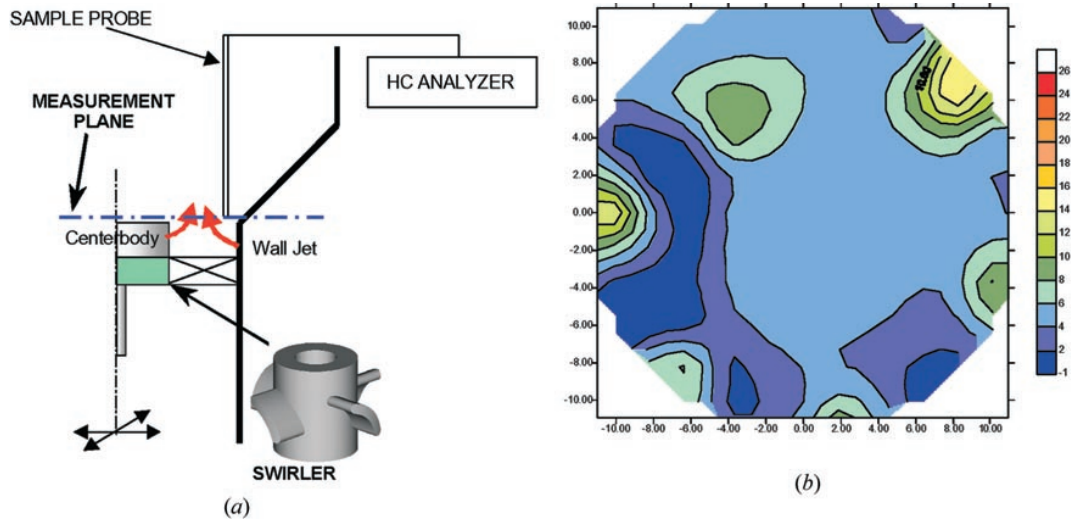


Figure 3. Fuel distribution (% HC) measurement using an extractive probe (700 K inlet temperature): (a) the injector configuration and measurement plane and (b) an example result, 0% centrebody, $\Phi = 0.47$.

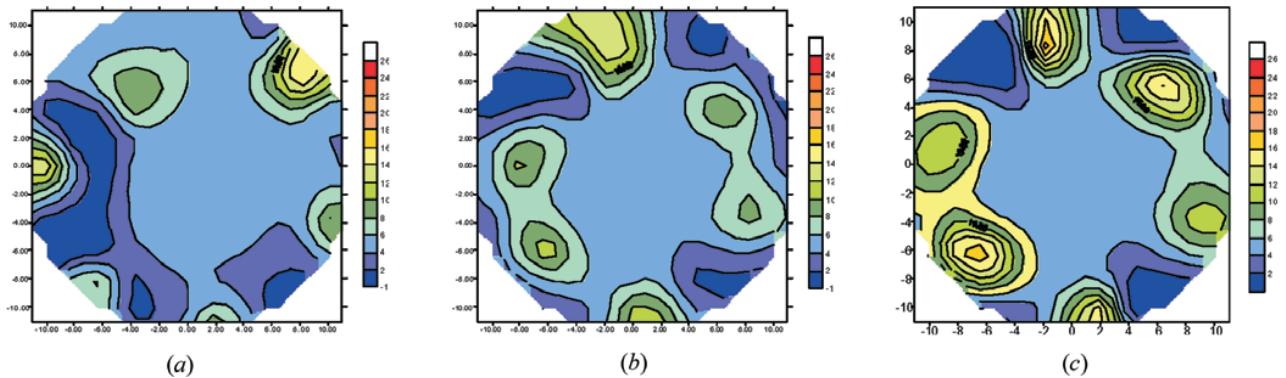


Figure 4. Fuel distribution (% HC) versus the percentage of fuel injected from the centrebody for $\Phi = 0.47$: (a) 0%, (b) 50% and (c) 100%.

can be utilized to measure the mixture ratio of two gases. To enhance the signal strength, it is beneficial to measure gases with a large variation in specific heat. In the fuel–air-mixing problem, for example, the ratio of the specific heats of methane and air is 2.2. In contrast, the specific heat ratio for hydrogen and air is 14.1 and that for helium and air is 5.2. The sensitivity of the hot-film strategy will thus be limited in the case of natural gas compared with a fuel replicant. The frequency response of this probe is rated up to 100 kHz and, with sufficient cooling of the probe, this strategy can also be applied to a high temperature environment. However, because it cannot distinguish between temperature and concentration changes, the hot-film probe cannot resolve fuel–air ratios in situations with temperature gradients in time and/or space.

2.1.2. Intrusive tracer-based methods. As an alternative to measuring the fuel directly using intrusive methods, it is also possible to dope the fuel stream with a tracer that can be measured by a sensor that would otherwise have been insensitive to the presence of fuel. The use of tracers such as inert gases and molecules with photo-physical properties that are well suited for optical methods will be addressed in section 2.1.4.

Few examples regarding the application of intrusive probes to measure tracers that track fuel–air mixing are available in the literature. The reasons are probably associated with the inherent desire to progress towards non-intrusive methods, as well as the introduction of complications that using a tracer produces by requiring an additional set of assumptions. Although most of this discussion focuses on tracer-based, non-intrusive methods, examples of intrusive tracer-based methods do exist. In particular, an intrusive probe not unlike that of Mongia *et al* (1996) has been developed with the purpose of providing an excitation wavelength and collecting the fluorescence signal from a point (Lee and Santavica 1997). In this case, acetone is seeded into the fuel stream to provide a convenient marker (this is discussed in more detail in section 2.1.4). With suitable calibration, this method obtains spatially and temporally resolved measurements of fuel tracer concentration, which can be further related to the local equivalence ratio. Although no results for an actual gas turbine combustor have been published, the strategy may have merit in practice.

An extractive probe that monitors the concentration of an inert gas species has been applied successfully to study mixing problems in gas turbines and, in particular, the jet

mixing aspects of these devices (Thayer and Corlett 1971, Rastogi and Whitelaw 1973, Khan and Whitelaw 1980). These methods rely upon the unreactive nature of helium, which acts as a passive scalar and can be readily measured using available analysers.

2.1.3. Non-intrusive non-tracer-based methods. Although intrusive methods can provide information relative to the mixing of fuel and air, non-intrusive methods for obtaining the same measurements are also available. Non-intrusive methods are more attractive due to their ability to extract measurements without actually contacting or disrupting the flow-field. The other potentially attractive aspect of non-intrusive methods is the ability to capture information in multiple dimensions (i.e. in a plane).

With the advent of laser-based diagnostics over the past 30 years, much effort has gone into the development and application of non-intrusive laser-based methods. Several excellent reviews which provide an overview of the various issues and experiences associated with these diagnostics are available (Eckbreth 1988, Chigier 1991).

Several laser-based strategies are available for application to quantification of fuel–air mixing in gas-fired gas turbine combustors. In practical gas turbine related systems, non-intrusive methods that assess fuel–air mixing must involve the characterization of natural gas or air. For natural gas, it is possible to utilize laser Rayleigh scattering, which is an elastic scattering process (i.e. the scattering occurs at the same wavelength as that of the incident beam). Detailed discussion of the theory behind Rayleigh scattering is available elsewhere in the reviews identified in the previous paragraph. The key issues with respect to practical applications, however, can be illustrated with a simple application. Consider for the moment an isothermal case involving a mixture of natural gas and air. In this case, the Rayleigh signal can be expressed in a simple manner as

$$I_R = K(\chi_a\sigma_a + \chi_b\sigma_b) \quad (2)$$

where K is a constant, χ_a is the mole fraction of air, χ_b is the mole fraction of natural gas, σ_a is the scattering cross section for air and σ_b is the scattering cross section for natural gas.

In this case, it is clear that a large differential cross section will result in the highest signal level. For natural gas, in which methane is the largest constituent, a scattering cross section of about $19 \times 10^{-28} \text{ cm}^{-2}$ is found (Muller-Dethlefs and Weinberg 1978), which is about 2.3 times larger than that of air. As a result, the sensitivity of the method for measurement of natural gas does not provide a large dynamic range of measurement. As with the hot-film strategy discussed in section 2.1.2 above, a system relying on Rayleigh scattering would benefit from a tracer (e.g. propane, which has a cross section that is about 15 times larger than that of air). Nonetheless, if the temperature of the system is fixed, the variation in signal will be attributable to the variation in the fuel concentration. This principle has been applied to the case of mixing fuel and air (e.g. Graham *et al* 1974, Escoda and Long 1983, Pitts and Kashiwagi 1984). However, Rayleigh scattering does have its limits for application

to complex practical devices. In particular, background scattering from particles or surfaces and luminosity from various sources lead to serious challenges with noise. As a result, Rayleigh scattering has not been widely applied to natural gas fired systems despite its benefit of not requiring a tracer.

The absorption strategy outlined in section 2.1.1 can also be used to assess the fuel distribution. The elements required for implementing this procedure imply the use of windows and line-of-sight transmission of a beam through the flow. Though the results from this method are not spatially resolved, the adequacy of the method can be determined from the application and the physical geometry of the device. For example, if the performance of a system over a period of time needs to be assessed, changes in the behaviour of the absorption can be monitored.

Spatial resolution can be attained from absorption measurements using tomographic strategies (Chen and Goulard 1976, Santoro *et al* 1981), but these require fairly extensive optical access in order to make the necessary multi-angular measurements. Furthermore, the use of tomography essentially eliminates any possibility of measuring temporally resolved information. Nonetheless, absorption methodologies can yield useful information regarding the distribution of natural gas, without using a tracer.

2.1.4. Non-intrusive tracer-based methods. Since the photophysical properties of natural gas limit application of optical methods, the vast majority of recent work in the area of measuring the mixing of fuel and air has relied upon seeding with a tracer or on replacing the fuel by a tracer in an effort to (i) increase the signal strength and (ii) reduce the noise associated with elastic scattering processes. As a result of the second issue, methods that result in a signal wavelength that is shifted from the original laser wavelength are preferred. Examples include laser-induced fluorescence and spontaneous laser Raman scattering. Many excellent review papers and books are available on these methods and the reader is referred to these offerings for details and discussions of their applications (Eckbreth 1988, Chigier 1991, Daily 1997).

For fuel–air mixing, several successful methods have been employed both for point and for planar measurements. Point measurements can utilize the same basic set-up as that for laser Rayleigh scattering, with the exception of the use of filters to isolate the red-shifted fluorescence from the elastic scattering. As a result, point measurements can be accomplished with a relatively straightforward set-up and with minimal optical access. The use of point-wise detectors also allows one to obtain high signal strength with relatively low-powered continuous lasers and allows the measurement of time series information which can be used to elicit the time varying mixing behaviour of the system.

To obtain planar information in highly turbulent flows, high-powered pulsed lasers are typically utilized in conjunction with highly sensitive area detectors to capture strong signal levels. As a result, the cost and complexity of the diagnostic becomes an issue. Though planar methods do provide a large amount of information, the qualitative nature

of such measurements often prohibits the acquisition of what might be termed 'comprehensive' information. Regardless of this issue, a remarkable number of tracer methods for the characterization of mixing has evolved. Some examples are provided in the following.

Some examples in the literature make use of scattering of light from fine particles to study mixing (Shaughnessy and Morton 1977, Long *et al* 1981, Clemens and Mungal 1991, Gullett *et al* 1993, Eaton *et al* 1996). In these cases, either small particles are seeded into the flow or particles are formed through a process occurring in the flow (e.g. titanium dioxide can be formed by reaction of titanium tetrachloride and water vapour). In the case of solid particles, it is often a challenge to introduce particles in a very steady and homogeneous manner. In addition, bias can be introduced due to temporal variation in the seeding density. Despite these issues, successful results have been obtained using basic scattering.

Gaseous species are easier to disperse into the flow than are solid particles. Nitrogen dioxide has been utilized for point measurements of mixing in a model gas turbine combustor. The methodology, which has been discussed in detail (Gulati and Warren 1994), is applied to quantify not only spatial variations in mixing but also temporal variations, which are then correlated to the combustion performance (Fric 1993). Although NO₂ has excellent photophysical properties for the study of mixing, its highly toxic nature may preclude its use in general applications.

Iodine has also been utilized for the measurement of mixing. Hiller and Hanson (1990) have reviewed the details of its use and historical applications in detail. Iodine has been utilized for the study of jet mixing applications (Hartfield *et al* 1989) and has also been utilized to measure a variety of other flowfield properties (Donohue and McDaniel 1996). Its use for gas turbine mixing applications has not been widespread. Part of the problem may be associated with the seeding strategies (sublimation) and with the corrosive nature of iodine. In addition, more convenient approaches have become popular.

Biacetyl has also been utilized for mixing studies (Yip *et al* 1988, van Cruyningen *et al* 1990). Not unlike iodine, however, widespread use of biacetyl fluorescence has not yet occurred, according to a review of the literature.

Perhaps the most widely used tracer for mixing studies is acetone. A detailed discussion of the principles and issues associated with use of acetone is provided by Lozano *et al* (1992). Acetone is excited over a wide range of wavelengths which allows relatively common lasers to be utilized (e.g. frequency quadrupled Nd:YAG lasers operating at 266 nm or excimer lasers operating at 308 nm). Relative to mixing studies for gas turbines, research has also been conducted to examine the photophysics of acetone at various temperatures and pressures (Grossmann *et al* 1996, Yuen *et al* 1997, Thurber *et al* 1998). These studies provide information that allows acetone PLIF to be utilized under conditions of elevated temperature and pressure. Recent work has utilized acetone PLIF to make measurements in practical devices in order to advance their design and/or operation (Stufflebeam *et al* 1999, Frazier *et al* 1998).

An example is shown in figure 5 for the same model combustor hardware as that with which the measurements

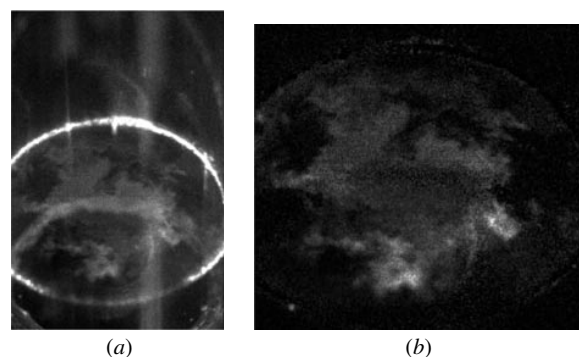


Figure 5. Instantaneous acetone PLIF images for the model combustor illustrated in figure 3(a): (a) without background treatment and (b) after background treatment.

illustrated in figure 3 were obtained. In this case a frequency quadrupled Nd:YAG laser (266 nm) was utilized to stimulate the acetone which was introduced through the fuel circuits. In figure 5(a), the distinct ring of bright light is due to the fluorescence of the quartz tube confining the flowfield. The lobe-like structure in the middle is produced by the fluorescence of acetone. By subtracting the background, the fluorescence associated with the 'fuel' is observed. Although this example is intended to be qualitative, the general structures are similar to those seen in figure 3(b).

With the advent of tracer-based methods, additional factors need to be considered. In complex systems with windows and other optical issues, strong mixing and associated dilution, signal strength is at a premium. In order to maximize signal levels, the tracer may, in fact, become a replacement. When another constituent is utilized to trace the fuel distribution, the scaling of the mixing becomes an issue. In many cases, advanced lean premixed concepts for gaseous fuel utilize discrete jet injection for the fuel. In jet mixing problems, the momentum ratio of the fuel stream and the stream into which the fuel is injected is a critical parameter (Patrick 1965). As an example, if the geometry illustrated in figure 3(a) utilized acetone instead of natural gas in order to study mixing behaviour, the jet penetration would vary. Figure 6 compares the results of using acetone matched with either the mass flowrate of natural gas or the velocity of the fuel jet. Alternatively, one could match the momentum flux ratio to obtain the same penetration, but this would result in a mismatch of Reynolds number, which is also important in the near-field mixing characteristics. As shown by the differences between the penetration curves in figure 6, the use of tracers requires considerable care.

For pure mixing applications, techniques such as Raman scattering can also be utilized; however, the signal strength is significantly lower than that of fluorescence or even Rayleigh scattering and, as a result, Raman scattering has not seen widespread use in mixing studies. Indeed, Raman scattering tends to be limited to applications in which practical geometries and situations do not complicate signal interpretation (Eckbreth 1988).

2.2. Liquid fuels

When liquid fuels are utilized, additional complexities are added to the overall process. Whereas gaseous fuels

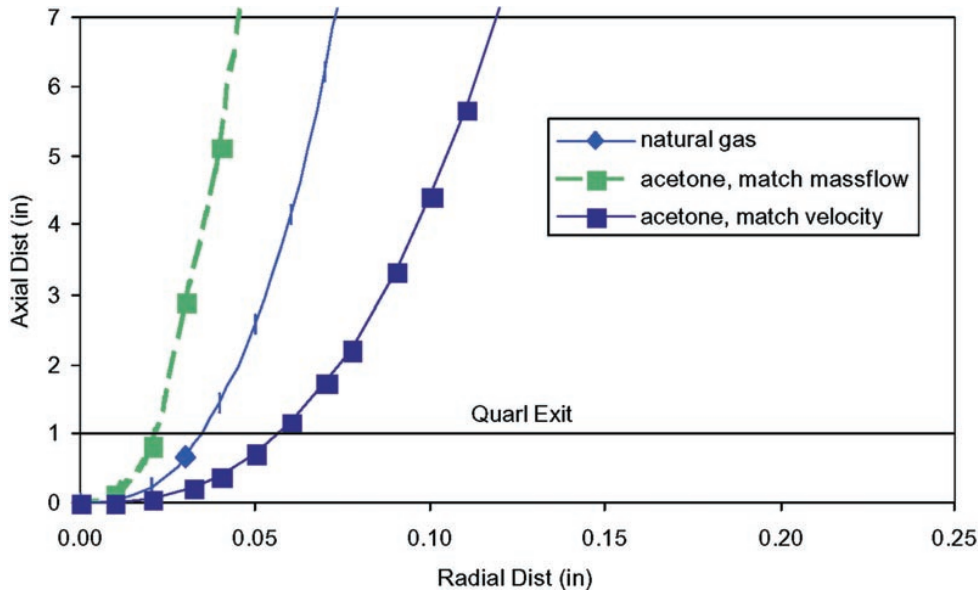


Figure 6. A comparison of calculated jet penetrations for natural gas and pure acetone for a radial injection system. The equivalence ratio for natural gas and air is 0.42 using the geometry in figure 2(a).

require time to mix and react, liquid fuels require the additional steps of atomization and vaporization. In addition, the heterogeneous system creates additional challenges and opportunities for performing measurements within the system. Liquid fuels are introduced into the combustor by a variety of mechanisms. Direct injection via an atomizer is the most common strategy. However, advanced concepts are relying upon partial or complete prevaporization of the fuel prior to its entry into the combustion chamber.

For assessing the mixing of the fuel and air, the measurement of the spatial (and/or temporal) distribution of mass is required. In the case of sprays, however, the presence of two phases for the fuel brings to attention the question of what should be measured. Ideally a method for measuring the fractions of vapour and liquid phases can be employed, although this will not be necessary in some cases. In a prevaporized system, for example, it is possible to utilize methods similar to those utilized for gaseous fuels, assuming that no droplets are present. However, in the case in which droplets are being examined, other methods for quantifying and also examining the evolving behaviour of the droplets are available. The approaches for examining fuel behaviour in the case of the two-phase flowfield are summarized in this section.

2.2.1. Patterning. Manufacturers of fuel injectors commonly conduct 'patterning' of sprays to ensure quality control, symmetry and the spray angle. Traditionally, these measurements have been conducted in the absence of reaction and also in the absence of the complex aerodynamics produced by the air flow required for combustion. Nonetheless, these measurements are typically required by the end user in order to ensure that the spray injector is performing as expected. These requirements are well founded in that intuition and experimental evidence have indicated that the spray pattern clearly influences the combustion performance (McDonnell *et al* 1996).

Mechanical devices have traditionally been utilized to measure the distribution of the spray in the flow. These devices may consist of a series of collection areas that are suddenly exposed to the spray and used to collect liquid over a fixed time. The volume (or mass) collected in each area can then be evaluated to assess the symmetry, spray angle and overall shape of the spray. These collection tubes have evolved into fairly sophisticated devices (McVey *et al* 1987). Mechanical devices have also been utilized to study spray patterns at elevated pressure (Cohen and Rosfjord 1991). Excellent examples that demonstrate the utility of advanced mechanical patternators for assessing the influence of hardware on spray behaviour are available in the literature (Cohen and Rosfjord 1993).

In addition to the use of mechanical devices, optical methods have also been applied in the area of spray patterning. In particular, laser-induced fluorescence has been applied to provide semi-quantitative mass distributions of the sprays. The methodology for application to liquid sprays is based on the same strategy as that for gas flows. Work in this area was pioneered by Melton (1983), who, in addition to applying this strategy to the liquid spray, added the ability to distinguish between the gaseous and liquid phases of the spray (Melton and Verdick 1984). This was accomplished by using 'exciplex fluorescence', in which the photophysical properties associated with specific combinations of molecules produce laser-induced fluorescence from the vapour phase that undergoes a lesser red shift than does that from the liquid. This method has been applied most commonly to automotive sprays and examples are found typically under the auspices of the SAE. A listing of work conducted until the early 1990s is available (Melton 1993), but few examples are to be found in the archived literature, and no example which utilized exciplex methods for gas turbines could be identified. One reason for the limited application of exciplex strategies in gas turbine applications is the role oxygen molecules play in the relative signal (i.e. the

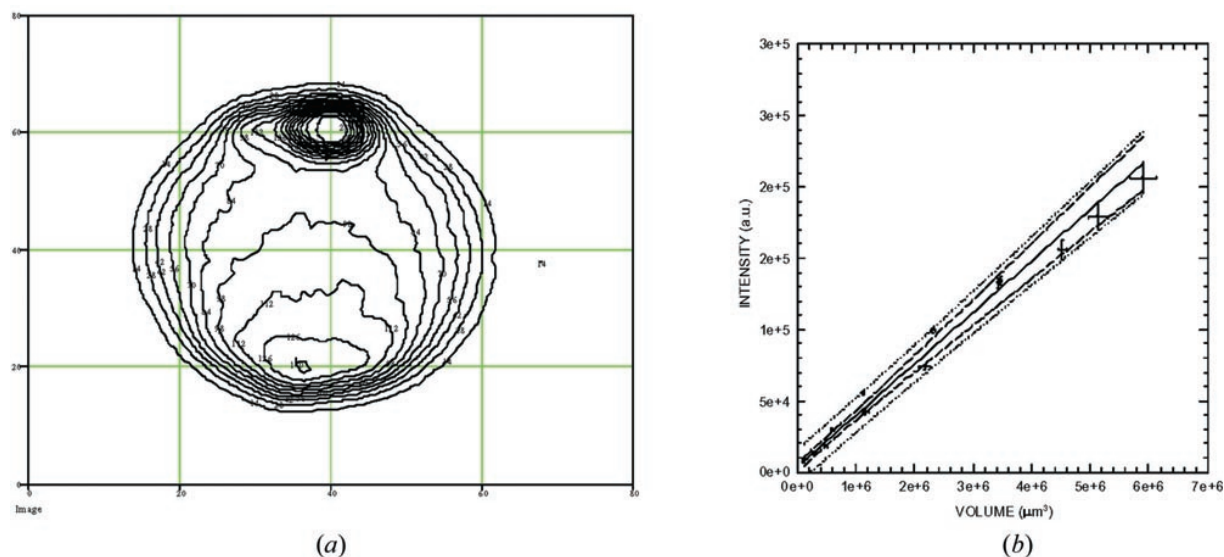


Figure 7. The relationship between the total integrated intensity and the droplet volume for optically thin monodisperse droplets (adapted from McDonell *et al* (1995)): (a) single droplet fluorescence intensity contours and (b) droplet volume versus the integrated intensity.

signal is quenched in the presence of oxygen). As a result, it is difficult to apply exciplex fluorescence techniques to general gas turbine systems. Recent work has taken advantage of the quenching to assess local fuel–air ratios in an oxygenated environment (Fröba *et al* 1998) and perhaps this will lead to additional studies in gas turbine applications. The chemical combination required to simulate the ‘fuel’ (including toxic substances such as benzene), however, may lead to similar practical limitations to, for example, those on the use of NO₂.

The early work by Melton led to additional work which examined the fluorescence of the liquid fuel only. As with the mechanical patternator, the basic liquid fluorescence technique provides information about the spatial distribution of the fuel. In early studies, the challenge of identifying complex chemical compounds and concerns regarding safety associated with use of exciplexes were overcome by the use of dyes and solvents which were compatible with a typical ‘open air’ test stand that might be utilized for the characterization of a fuel spray. Some early examples include studies by McDonell *et al* (1996) and Chung *et al* (1997). In both of these cases, a fluorescein dye was doped into methanol and the spray was excited with an Ar⁺ continuous wave laser. The doping process for such methods, however, must be carefully controlled. If the absorption of the laser light is so great that it cannot excite the molecules throughout the droplet, the subsequent fluorescence will not be proportional to the volume and the resulting image will not provide information about the mass distribution. Figure 7(a) illustrates the desired behaviour relative to the fluorescence intensity. In this case, the laser sheet is introduced from the bottom of the page. The droplet fluorescence is shown in the contours. The far side of the drop has a local maximum, which corresponds to the focusing of the laser light by the droplet curvature. Despite the non-uniformity of the fluorescence emission from the droplet, the relationship between the total integrated intensity (i.e. the sum of the intensities from the image shown in figure 7(a)) and volume is linear for this case of optically thin droplets (figure 7(b)).

In a system in which the dye can be introduced into the solvent, this problem can be overcome easily. However, it would be very beneficial from a practical perspective if the addition of dyes or other chemical compounds could be avoided.

For many practical distillate fuels, there are compounds within the fuels which fluoresce when they are excited by short wavelengths of light. This behaviour is typical of many aromatic compounds, whose absorption occurs in the ultraviolet range. As a result, solid state lasers with UV wavelengths (e.g. frequency tripled or quadrupled Nd:YAG lasers) can be utilized. However, as with the use of dyes, care must be taken to assess the relative absorption in order to ensure that the system is optically thin so that the image will be a direct measure of the fuel mass distribution. Good examples that illustrate a non-mass-related image are found in Bazile and Stepowski (1995) and Le Gal *et al* (1999), in which images of droplets that are optically thick are shown in a manner similar to figure 7(a). In these cases, the laser light may penetrate only into the first few micrometres of the droplet surface before being completely absorbed!

Examples of planar liquid laser-induced fluorescence (PLLIF) applied to map out the fuel distribution for gas turbine applications are now available in the literature (McDonell *et al* 1996, Locke *et al* 1998, Ateshkadi *et al* 1998). In the case of McDonell *et al* (1996), a direct correlation between the statistical interpretation of the spray distribution and the combustion performance is made. This result reaffirms the utility of inferring fuel–air mixing behaviour from the measurement of the spray distribution. In the case of Ateshkadi *et al* (1998), the results obtained using PLLIF to determine the fuel distribution were correlated to several aspects of combustion performance, including stability and emissions. Hence, the ability to assess the uniformity of the fuel distribution via the spray droplets does provide an indicator of how fuel–air mixing relates to combustion performance.

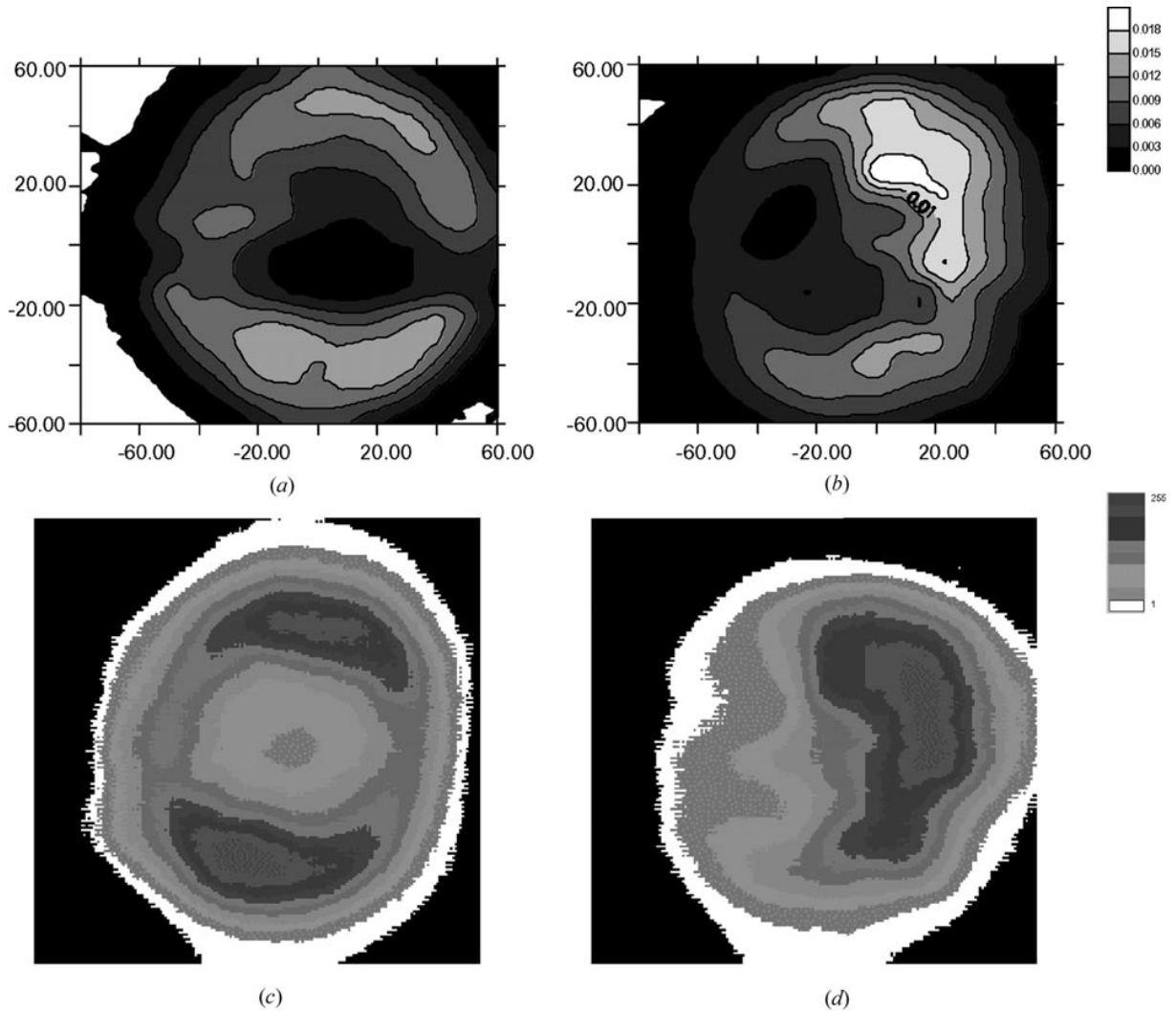


Figure 8. A comparison of the volume flux ($\text{cm}^3 \text{cm}^{-2} \text{s}^{-1}$) from PDI and the intensity concentration (grey level) from PLLIF for two combustor injectors/swirler configurations at axial distance $Z = 50 \text{ mm}$ from the injector exit plane (adapted from McDonnell *et al* (1996): (a) configuration 1: PDI; (b) configuration 1, PLLIF; (c) configuration 2, PDI; and (d) configuration 2, PLLIF.

In each of these cases, no consideration was given to the issue of laser attenuation, which can lead to perceived asymmetry. Since the excitation light source is scattered by droplets as it enters the spray, droplets on the far side of the spray relative to the laser sheet will receive less incident light and therefore generate less fluorescence. Several methods that have been developed to help address this problem are beginning to appear (Talley *et al* 1995). Examples of using PLLIF to detect fuel in reacting sprays are also to be found in the literature, although many assumptions which make it nearly impossible to obtain quantitative results in these situations are made (Locke *et al* 1998, Allen *et al* 1995).

2.2.2. Phase Doppler interferometry. Phase Doppler interferometry (PDI) provides extensive information about the behaviour of sprays from point-specific, simultaneous measurements of droplet size and velocity (Bachalo and Houser 1984). The PDI measurements provide information on the liquid volume (from the droplet size) and the time between arrivals of droplets. In addition, with some

estimation of the laser beam sampling volume, an estimation of the liquid mass flux can be made (Qiu and Sommerfeld 1992). This method has been applied extensively world wide and is commonly utilized for detailed spray measurements. Discussions regarding the measurement issues associated with this method are available elsewhere (Bachalo and Houser 1984, McDonnell and Samuelsen 1995a).

PDI is not ideally suited for the study of spatial fuel–air mixing in that, since it is a point measurement, the mapping of information over a plane can be tedious. However, the added information on droplet size and velocity may well make the extra effort worthwhile, depending upon the application. Indeed, the study of transport of the fuel requires knowledge of the droplet sizes and velocities. For an assessment of fuel–air mixing, PDI can be utilized in a manner similar to PLLIF. Figure 8 shows an example of results obtained for two combustor fuel injection systems. In this case, the PDI and PLLIF results reveal similar overall features of the spray mass distribution. This comparison also helps to reaffirm the utility of the PLLIF results.

2.2.3. Droplet sizing. Although the droplet size is not a direct indicator of fuel–air mixing, it is a critical parameter associated with any liquid fuel system. The droplet size will play a key role in the vaporization process and may lead to fundamental constraints on the geometry of hardware being developed for the express purpose of mixing. In addition, in the case of droplet transport, the droplet size must be known in order to determine how the droplet will be convected by the continuous phase. Hence, some discussion on droplet size is provided here, even though it is not a direct measure of mixing.

As mentioned above (section 2.22), PDI is a well-established method for the measurement of droplet size and velocity. Although it was described in the previous section in the context of fuel volume flux measurements, PDI is used to directly measure the droplet size.

In addition to point measurements of droplet size, planar methods are now starting to be developed and applied. The basis for the use of planar methods is a combination of scattering (proportional to the droplet surface area) and fluorescence (proportional to the droplet volume if certain criteria are satisfied). The ratio of the fluorescence to scattering, therefore, should be proportional to the Sauter mean diameter (or D_{32})[†]. The performance of the diagnostics that provide D_{32} distributions across a plane has been demonstrated only very recently (Sankar *et al* 1999, Locke *et al* 1998, Le Gal *et al* 1999). An example is shown in figure 9 for an air-assisted plain-jet atomizer measured 10 mm below the injector exit plane. In this case, the ratio of fluorescence to scattering is presented together with discrete circles, which reflect the D_{32} (concentration weighted) measured via PDI. The results are shown for three drops in atomizing air pressure (of 2, 4 and 6%). It is well established that, as the atomizing drop in air pressure (and hence the mass flow) increases, the droplet sizes will decrease. This is reflected both in the PDI and in planar methods for size measurement.

The strategy for using planar methods for measuring droplet size appears well founded and their application has been demonstrated for basic sprays as well as for a complex flow application (Locke *et al* 1998). The results for the basic sprays appear quite consistent and promising. The results for the complex reacting sprays appear much less clear. Indeed, the difficulties raised with respect to temperature dependencies and multi-component fuels must be further evaluated before planar droplet sizing methods can be applied in general to complex sprays.

2.2.4. Phase discrimination. As mentioned above, the measurement of fuel–air mixing in fuel sprays is complicated by the potential need to discriminate the vapour phase from the droplet phase. The assessment of vapour is important because the mixture of vapour and air is the mixture that actually combusts. As a result, the ability to determine the local fuel–air ratio on the basis of the measurements of the vaporized fuel and air is greatly desired.

Intrusive methods have been developed specifically to address the discrimination of phases. The most recent

application discussed in the literature appears to be that of Dodge and Moses (1984). In this case, an aerodynamic separation strategy is utilized to sample vapour within a spray using an extractive probe in a manner similar to that described in section 2.1.1. Although the results appeared satisfactory in that study and the few examples that preceded it, widespread use of these probes has not appeared in the more recent literature.

Another strategy for measuring the vapour concentration in the presence of droplets is the use of light extinction. By using absorption lines at 3.39 μm for hydrocarbons in conjunction with a non-absorbing wavelength (e.g. 0.6328 μm) the vapour concentration along a line of sight can be deduced. Since the droplets scatter both wavelengths, but only the 3.39 μm wavelength is absorbed by vapour, the relative transmission of the two wavelengths yields the amount of extinction due to the presence of the vapour. This approach was developed by Chraplyvy (1981) and further analysed and extended by Adachi *et al* (1991) and Drallmeier and Peters (1991). In each case, deconvolution of the measurements was applied to retrieve spatially resolved information. Suzuki *et al* (1994) did some additional work using this differential absorption strategy, whereby additional tomographic techniques were employed to recover spatially resolved information for non-axisymmetrical sprays.

Planar methods for measuring vapour in the presence of droplets have already been described in section 2.2.1 in the discussion of exciplex fluorescence. Non-exciplex strategies have also been utilized. In particular, Bazile and Stepowski (1995) utilized a combination of scattering and fluorescence in conjunction with fairly elaborate image processing to characterize the vapour and liquid phases in an acetone spray. In this case, the signals from isolated droplets could be evaluated. This would seem to limit the strategy to dilute sprays. Bazile and Stepowski (1994) also utilized a combination of Raman scattering and laser induced fluorescence to evaluate the relative concentrations of vapour and liquid. The key strategy involved the assumption that the Raman signal would be proportional to the total liquid volume whereas the fluorescence, with the dye–solvent system utilized, would be proportional to the original volume. This technique assumed that the dye would not vaporize with the fuel, but rather would remain dissolved in the liquid in its original quantity, thereby maintaining the total number of dye molecules independently of vaporization.

In addition to phase discrimination associated with the fuel, it is also possible to discriminate between the fuel (regardless of phase) and the continuous phase. This has been done for reacting flows (Allen *et al* 1995) for which, in addition to the imaging of the fuel concentration, the imaging of other species (e.g. OH) can be used to deduce the relative location of the fuel and the reaction zone.

Another possibility, which is of interest regarding the injection of liquid fuel, is the relative behaviours of the liquid fuel and the atomizing air. This is of interest in that the fidelity of the droplet behaviour with the aerodynamics can be evaluated. Figure 10 shows an example for the same plain-jet air-blast atomizer as that considered in the results shown in figure 9. In figure 10, a careful combination of filters allows the isolation of the atomizing air seeded with

[†] Given by $D_{32} = \frac{\sum n_i D_i^3}{\sum n_i D_i^2}$.

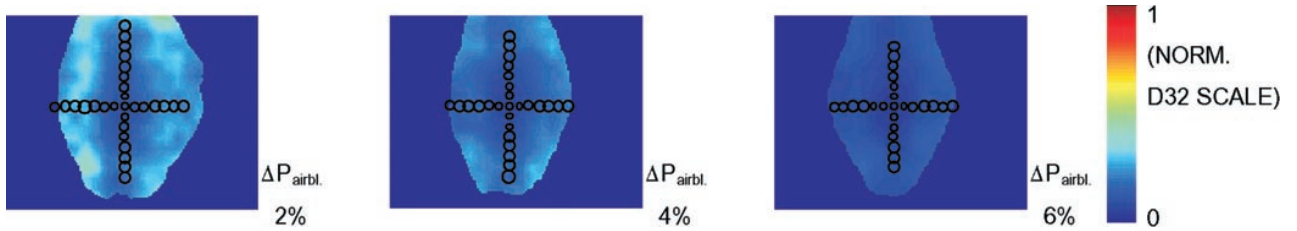


Figure 9. A comparison of the ratio of fluorescence and scattering images with PDI-measured D_{32} values for various atomizing drops in air pressure (adapted from Leong *et al* (2000)).

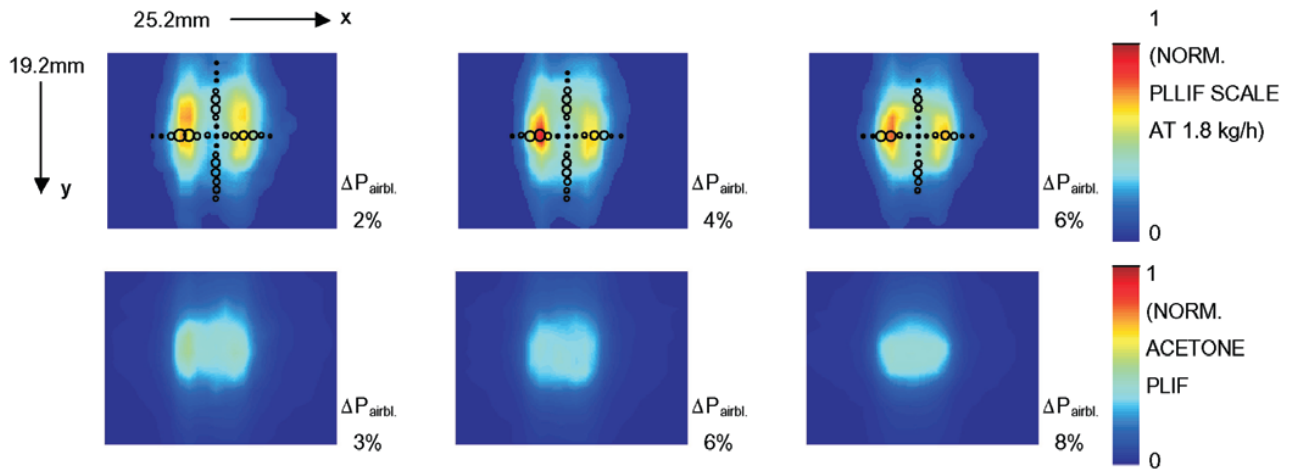


Figure 10. A comparison of the liquid mass distribution (top row) and the atomizing air concentration (lower row) for plain-jet-air-assisted atomizer (diameters of circles in the top row correspond to PDI profiles of liquid volume concentrations) (adapted from Leong *et al* (2000)).

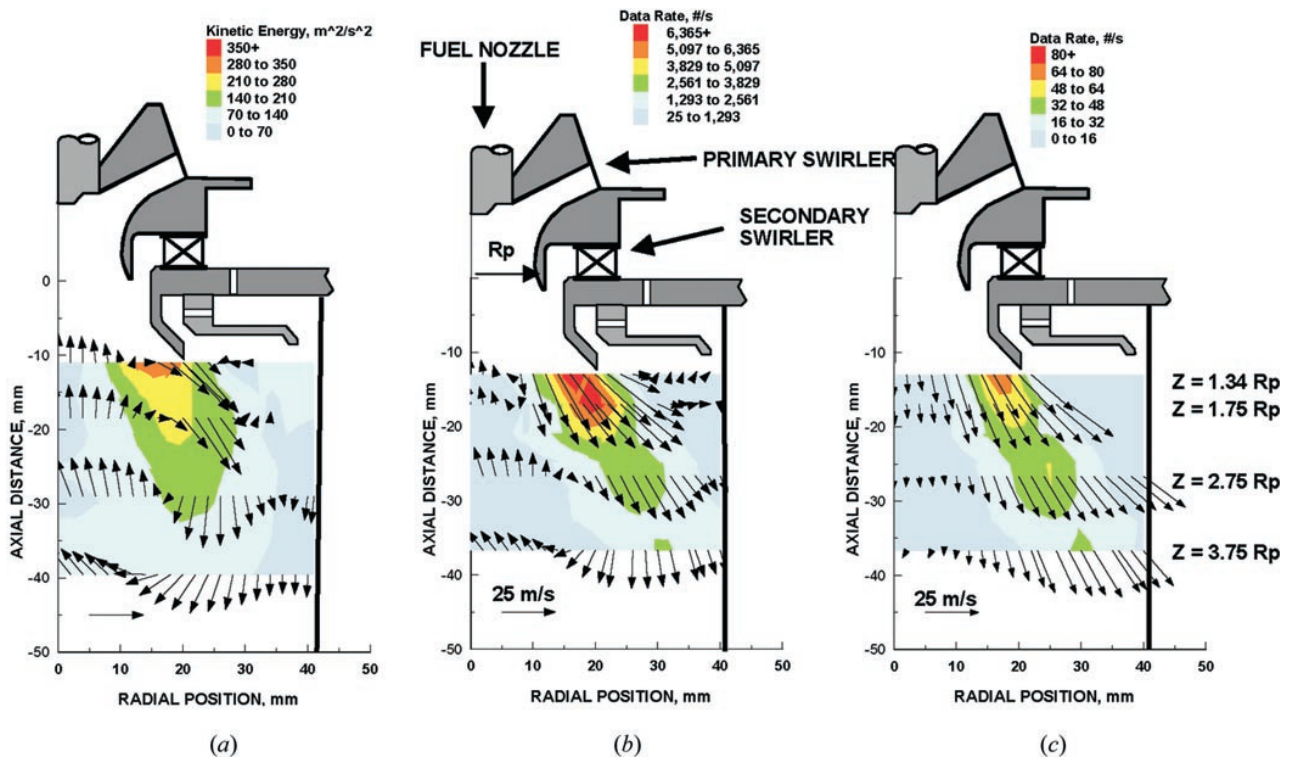


Figure 11. A comparison of the gas phase velocity, turbulent kinetic energy, velocity and population of two droplet size classes for a production gas turbine engine dome assembly: (a) gas phase, (b) particles of 11–20 μm diameter and (c) particles of 76–90 μm diameter.

acetone and the hydrocarbon liquid fuel excited at the same wavelength. In figure 10, the mass distribution of liquid is shown 10 mm downstream of the injector in the top row of images for three atomizing drops in air pressure (of 2, 4 and 6%). The air is introduced from two opposite, discrete injection ports (corresponding to left-hand and right-hand sides of the images), which causes the two-lobed structure revealed by the PLLIF. Overlaid upon the images are discrete circles. The diameter of the circles corresponds to the volume concentration measured by PDI. The correspondence between PDI and PLLIF is again quite consistent (recall figure 8). In the lower row of images in figure 10 are the corresponding PLIF images associated with the atomizing air. In this case, the acetone fluorescence is being utilized to deduce where the bulk of the atomizing air is going and to establish the comparative dispersion of the droplets and the air.

It is noteworthy that the methods for discriminating phases have not been utilized to obtain measurements in highly complex practical devices. Indeed, many assumptions about interference, noise and signal proportionality are required in order to make the results even semi-quantitative. As a result, it is likely that these methods will not be utilized in a widespread manner outside research oriented facilities. Although this is not necessarily a shortcoming, the application of these methods and strategies on a regular basis in a production type of environment without experienced personnel will be very challenging and requires considerably more development effort.

3. Flowfield transport

The assessment of the transport of the fuel-air mixture requires knowledge of the aerodynamics of the combustion chamber. In the case of gaseous fuels, the transport following injection will be tied to the physical properties such as the turbulent Schmidt number. In these cases, detailed knowledge of the continuous phase flowfield allows the interpretation of the direction and velocity at which the fuel is being transported. In the case of liquid fuels, the transport is more complex. This is associated with the relative strength of the droplet momentum and body forces (e.g. droplet drag) which depend upon the size of the droplet and the velocity of the droplet relative to the continuous phase. These issues are discussed in detail elsewhere (Sirignano 1993, McDonell and Samuelsen 1995b, Faeth *et al* 1995).

Regardless of whether the fuel is present in the form of droplets or gas, an understanding of the transport issues requires the delineation of the flowfield characteristics. As a result, a discussion of approaches used to accomplish this is provided here. In general, the need to delineate the flow vector and scalar fields is evident.

3.1. Vector fields

The measurement of the velocity field in complex combustion systems has evolved from point measurements (i.e. laser anemometry) to planar measurements (i.e. particle image velocimetry and Doppler global velocimetry). Multiple components of the velocity can be measured using either method.

3.1.1. Laser anemometry. Laser anemometry is a very well-established technique in which two laser beams of the same frequency are crossed in space to form an interferometric sample volume (Yeh and Cummins 1964). Fine particles are 'seeded' into the flowfield and, when they scatter light from the region in which the beams cross, the light is collected using sensitive detectors and the signal generated is subsequently analysed for frequency characteristics which are then related to the velocity. The technique is ubiquitous in its application to complex flows, so the reader is directed elsewhere for its history and evolution (Durst *et al* 1976, Thomson and Stevenson 1979, Chigier 1991).

The use of laser anemometry in complex flows was extended to sprays in 1984 with the advent of PDI, which was discussed previously in section 2.2.2. An illustration of the type of results that can be obtained is shown in figure 11, in which the detailed flowfield and spray behaviour downstream of a production gas turbine combustor dome are shown. In this example, the combustor is liquid fired. As a result, PDI has been applied in parallel with LA to delineate the droplet behaviour. Figure 11(a) shows the gas phase mean axial velocity vectors in the r - Z plane with contours of the gas phase turbulent kinetic energy. Figure 11(b) and (c) show the mean velocity vectors in the r - Z plane and contours of the population of droplets for an 11–20 μm -diameter range and a 76–90 μm -diameter range, respectively. Several key points are illustrated by the results. First, the gas phase features a strong on-axis recirculation zone, which is bounded by regions of strong turbulence. The flow generated by the mixer actually impinges on the combustor wall, which results in an acceleration of the flow in the downstream direction at the wall. The combustor dome also generates a corner recirculation zone. These features give a clear impression of the actual flowfield that this production device provides. In the case of gaseous fuel, it would be possible to apply a technique like acetone PLIF to mark the path of the fuel and to observe the degree of its mixing (Frazier *et al* 1998). In the liquid fired example shown in figure 11, PDI is utilized to delineate the droplet behaviour. Two size classes are shown for comparison. The fine droplets tend to follow the gas phase associated with the relatively small mass of these droplets. Also, the PDI illustrates where these drops are found (i.e. the largest population of droplets is found at a location corresponding to the region of most intense mixing in the gas phase). The larger droplets penetrate the gas phase flowfield and behave ballistically in impinging on the wall. Figure 11 illustrates the type of detailed results made possible by LA and its extension, PDI, and confirms the power of these methods for illustrating the flowfields and transport of material within the combustion chamber.

3.1.2. Particle image velocimetry. Particle image velocimetry (PIV) evolved from a desire to rapidly obtain the type of information shown in figure 11. In addition, the point measurements provided by LA, despite providing substantial information from a statistical point of view (i.e. distribution means, the standard deviation, skewness, etc), cannot resolve the large structures present in the flow. The development

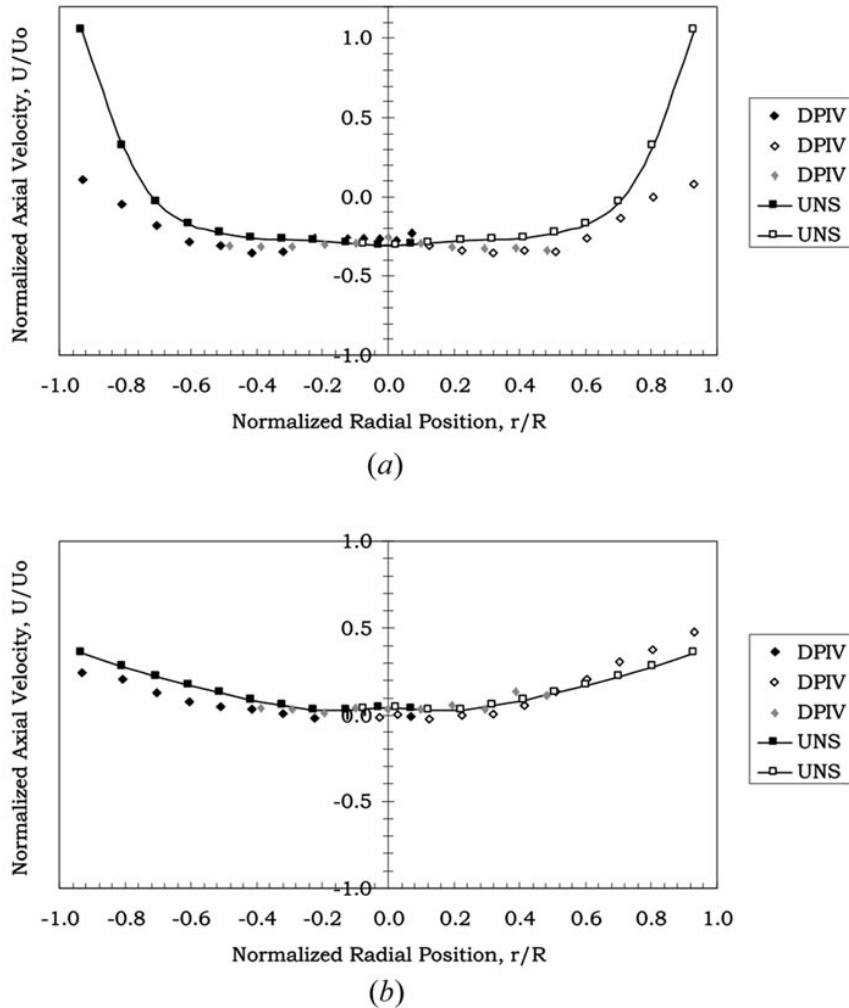


Figure 12. Examples of DPIV results from a swirl-stabilized combustor compared with CFD modelling simulations at two axial locations: (a) $x/D = 0.75$ and (b) $x/D = 2.83$.

of PIV began in the late 1970s, with the work of Grousson and Mallick (1977), Simpkins and Dudderar (1978), Barker and Fournery (1977) and others, and has been extensively researched since (Meynart 1983, Grant and Smith 1988, Keane and Adrian 1990, Willert and Gharib 1991, Mungal *et al* 1995, Adrian 1996). PIV is a diagnostic technique that measures instantaneous flow-field velocities over a two-dimensional plane. This is accomplished by recording, during successive periods, the positions of small particulate markers suspended in the fluid during successive periods. These small particles are illuminated for a short period (to freeze the motion of the flow) by using a high-energy light source such as a pulsed laser. A set of images (generally two) is recorded using a succession of light pulses. The light scattered from the particles is recorded and analysed. Whereas early PIV methods relied upon film, the advent of high resolution digital cameras in the early 1980s has allowed a digital version of PIV (digital particle image velocimetry (DPIV)) to be developed. This has the potential for widespread use in a variety of commercialized systems. Only recently have the cost/performance issues related to immense data storage requirements, camera resolution and

laser light sources been resolved in order to facilitate its application to complex flows found in combustors.

Recent developments in PIV include stereo methods, which allow three velocity components to be measured instead of only two (Soloff *et al* 1997). Although this requires the use of multiple cameras, the past five years have seen developments in digital cameras that allow cost-effective strategies to be developed.

To illustrate the potential of DPIV, figure 12 presents comparisons of DPIV measurements with CFD calculations (FLUENT UNS) in a swirl-stabilized combustor at two axial locations (Shaffar 1997). The measurements in this case were made in a circular quartz tube and therefore required considerable treatment of the DPIV images in order to account for distortion near the walls. The results illustrate the ability of the method to measure profiles provided by LA that are obtained within a matter of minutes rather than hours.

3.1.3. Other field velocity measurements. Other planar methods for the measurement of velocity have been developed during the 1990s. These methods generally involve a set-up not unlike that for DPIV or stereo DPIV.

The difference between these newer methods and PIV is the use of the spectral shift of the imaged light, which can then be utilized to deduce the velocity. Most of the applications in which these other methods have been utilized involve very high-speed flows (e.g. $>100 \text{ m s}^{-1}$). In some cases, particles are seeded into the flow and the relative frequency shift of the scattered light is determined by using a molecular filter that transmits as a function of the frequency of the light in a carefully calibrated fashion (Devlin *et al* 1971). An example of a method in which seeding is utilized is Doppler global velocimetry (DGV) (Meyers and Komine 1991, Elliott *et al* 1994, Roehle 1997). Roehle (1997) shows examples in which DGV has been applied using an argon-ion laser and an iodine filter to characterize the three-dimensional velocity field generated by a gas turbine fuel injector not unlike that shown in figure 11. For flowfield velocities that are not as extreme as those found in many other applications, the results from DGV look quite promising.

Efforts have also been directed at strategies in which seeding is not required. In this case, a laser is again utilized, but it is used to excite molecules that are already present in the flowfield rather than relying upon scattering from foreign particles. Examples include RELIEF (Miles *et al* 1989, Pitz *et al* 1996) and filtered Rayleigh scattering (FRS) (Forkey *et al* 1996). An overview of the history and evolution of these methods is provided in Forkey *et al* (1998).

For the application to gas turbine combustion, in which total velocities typically are below 100 m s^{-1} , laser anemometry is well established. DPIV for reacting flows in general has not been demonstrated extensively, and requires fairly high powered lasers to get reasonable signal-to-noise ratios, even in complex non-reacting flows. DGV may be possible for reacting systems, but has not been investigated extensively. The recirculating flows found in gas turbine combustors lead to regions of near zero velocity components and thus may pose questions regarding accuracy for DGV.

3.2. Scalar fields

In addition to vector fields, additional insight into mixing behaviour may also be gained by the measurement of scalar fields including species and temperature. The measurement of species may be achieved using the same approaches as those employed in measuring fuel mixing behaviour, namely laser-induced fluorescence both in point and in planar forms. These methods have been discussed briefly here and in detail elsewhere within this issue (Laurendeau 2000).

The measurement of temperature may be of interest relative to mixing and heat release. This can also be done using fluorescence methods. Other strategies including coherent anti-Stokes Raman spectroscopy (CARS) can also be applied (Eckbreth 1988).

4. Summary

An overview of measurement practices for the delineation of fuel-air mixing and transport in gas turbine combustion has been provided. The summary is divided into applications for gaseous fuels and liquid fuels since most of the diagnostics developed are specific to the phase of the fuel. Many

possible methods for assessing the general mixing have been developed, but not all have been applied to practical systems either under scaled or under actual conditions. For gaseous mixing processes, acetone PLIF appears to be finding general acceptance and application in actual systems. Spray-fired systems have seen the proliferating application of PDI in practical devices and under practical conditions, while planar laser-induced fluorescence approaches are beginning to be implemented in more applications. In terms of delineating the vector fields associated with the process of mixing, laser anemometry, although it is tedious to apply, has proven reliable. Newer methods such as DPIV and FRS have seen only limited application in practical systems. In terms of scalar fields, LIF has successfully been applied to practical systems.

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