Mole-Fraction-Sensitive Imaging of Hypermixing Shear Layers

J. S. Fox* A. F. P. Houwing† and P. M. Danehy‡
Aerophysics and Laser-based Diagnostics Research Laboratory
Department of Physics and Theoretical Physics
Australian National University
Acton, A.C.T. 0200, AUSTRALIA

M. J. Gaston§ N. R. Mudford∥ and S. L. Gai∥∥
Department of Aerospace and Mechanical Engineering
University College
University of New South Wales
Campbell, A.C.T. 2612, AUSTRALIA

A theoretical model that determines the optimum excitation frequency for obtaining a fluorescence signal with a strong dependence on fuel mole-fraction is presented for supersonic fuel-air compressible mixing studies. The challenge associated with this is to maintain a high sensitivity to fuel mole-fraction with minimal sensitivity to temperature and pressure in a flow with large temperature variations and pressure gradients. The results of the model are applied to the mixing region behind various scramjet fuel injectors in a shock tunnel to measure fuel mole-fraction. Hydrogen fuel at a Mach number of 1.7 is injected into a mostly N₂ free stream at Mach 4.8. Experimental fluorescence images are presented in streamwise and spanwise planes.

Nomenclature

- \( c_p \): Specific heat capacity at constant pressure, J.kg\(^{-1}\)
- \( c_p,\infty \): Specific heat capacity of pure freestream, J.kg\(^{-1}\)
- \( c_{p,\text{fuel}} \): Specific heat capacity of pure fuel stream, J.kg\(^{-1}\)
- \( f^* \): Boltzmann fraction of the absorbing state
- \( g \): Spectral overlap integral, 1/cm\(^{-1}\)
- \( g_a \): Absorption line shape, 1/cm\(^{-1}\)
- \( g_l \): Spectral profile of laser, 1/cm\(^{-1}\)
- \( k \): Boltzmann’s constant, J.kg\(^{-1}\)
- \( m_{\text{NO}} \): Molecular mass of NO, kg
- \( m_p \): Molecular mass of perturbing species, kg
- \( A \): Effective spontaneous emission rate, s\(^{-1}\)
- \( A_{\text{las}} \): Cross-sectional area of the laser sheet, m\(^2\)
- \( C_{\text{opt}} \): Overall conversion efficiency, dimensionless
- \( E \): Energy of rotational state, J
- \( E_p \): Laser energy per pulse, J
- \( J^* \): Rotational quantum number
- \( K \): Fluorescence signal per mole-fraction of fuel, counts
- \( K_{\text{max}} \): Maximum fluorescence signal per mole-fraction of fuel, counts
- \( P \): Pressure, Pa
- \( Q \): Total collisional quenching rate, s\(^{-1}\)
- \( S \): Fluorescence signal, counts
- \( S_{\text{max}} \): Maximum fluorescence signal, counts
- \( T \): Temperature, K
- \( T_{\infty} \): Temperature of pure freestream, K
- \( T_{\text{fuel}} \): Temperature of pure fuel stream, K
- \( T_{\text{mix}} \): Temperature of fuel-freestream gas mixture, K
- \( \chi_a \): Mole-fraction of the absorbing species
- \( \chi_p \): Mole-fraction of perturbing species
- \( \chi_{\text{fuel}} \): Fuel mole-fraction
- \( \delta_\phi \): Uncertainty in fluorescence signal due to \( \delta_\chi \), counts
- \( \delta_\phi \): Uncertainty in fluorescence signal due to \( \delta_\chi \), counts
- \( \psi_{\text{NO}} \): Thermal velocity of NO, ms\(^{-1}\)
- \( \eta(\sigma) \): Total quenching cross-section, m\(^2\)
- \( \eta(\sigma) \): Quenching cross-section of perturbing species, m\(^2\)

Subscripts

- \( i \): Freestream
- \( j \): Subscript for labelling generalised parameter
- \( \text{fuel} \): Fuel
- \( \text{max} \): Maximum value
- \( \text{NO} \): Nitric oxide
- \( p \): Perturbing species

Superscripts

- \( l \): Lower laser-coupled state

Introduction

A proposed propulsion system for the next generation of aerospace planes is the supersonic combustion ramjet (scramjet). It is perhaps the most promising candidate for an air-breathing engine capable of operating at hypersonic speeds. One of the challenges associated with the design of a successful prototype scramjet is the requirement to achieve a sufficiently high degree of mixing between the fuel and air so that the injected fuel undergoes combustion prior to its expulsion from the vehicle.

It is well known that mixing of air and fuel at supersonic speeds is not efficient.¹ Mixing enhancement is therefore necessary to ensure that combustion occurs sufficiently rapidly to provide adequate
thrust. This can be assisted by fuel injector design. One method of mixing enhancement that is being investigated is termed hypermixing, with fuel injectors that employ this method being called hypermixers. Hypermixers generate streamwise vorticity that increases the surface contact between the fuel and air streams. The aim of this investigation is to quantitatively and qualitatively study the performance of such hypermixing fuel injectors using an instantaneous, quantitative planar laser-induced fluorescence (PLIF) mole-fraction imaging technique. Many traditional line-of-sight techniques have been used to study scramjet fuel injectors including schlieren, shadowgraph, and interferometry. However, these methods are limited to measurement of integrated properties along the line-of-sight. By contrast, PLIF is suitable for both qualitative flow visualisation and quantitative measurement of complex three-dimensional flow fields. This technique provides species and quantum-state specific information with very good spatial and temporal resolution.

PLIF involves illuminating the flow with a thin sheet of laser light tuned to excite electronic transitions in a chemical species in the flow. Here, the species is nitric oxide (NO), which is a minor component in the flow being studied. The fluorescence induced by this illumination is focussed onto an intensified charge-coupled device (ICCD) camera to produce an image of the fluorescence in that region. With judicious choice of transition and subsequent image processing, the technique can yield measurements of temperature, pressure, velocity, and interferometry. However, these methods are limited to measurement of integrated properties along the line-of-sight. By contrast, PLIF is suitable for both qualitative flow visualisation and quantitative measurement of complex three-dimensional flow fields. This technique provides species and quantum-state specific information with very good spatial and temporal resolution.

The PLIF signal is a function of temperature, pressure, species concentrations and a number of known experimental parameters. To directly measure the fuel mole-fraction, a strategy must be developed to minimize the temperature and pressure dependencies of the PLIF signal. This can be achieved by the choice of gases used in the free stream and fuel, and by choosing a laser frequency and linewidth which simultaneously excites both low- and high- J transitions.

The work reported here centers around the attempt to visualise the fuel mole-fraction in the presence of pressure gradients and large temperature variations. This method is demonstrated through the investigation of mixing layers behind hypermixing fuel injectors injecting fuel into a Mach 4.8 co-flowing free stream, with a convective Mach number of 0.64.

**PLIF Theory**

Fluorescence signal

The PLIF signal is a function of counts recorded on a pixel of a detector) is a function of temperature, pressure, mole-fraction and a number of other known experimental parameters. Provided the assumptions of linear fluorescence, weak excitation, negligible laser beam attenuation, and negligible radiation trapping are valid, the fluorescence signal level is given by:

\[
S = \frac{E_p}{A_{\text{abs}} kT} \chi_k P \sum_i [f_i J''] B g_i \left( \frac{A}{A + Q} \right) C_{\text{opt}} \tag{1}
\]

where the summation is over all transitions; \(E_p\) is the laser energy per pulse; \(A_{\text{abs}}\) is the cross-sectional area of the laser sheet; \(\chi_k\) is the mole-fraction of the absorbing species; \(P\) is the pressure; \(k\) is Boltzmann’s constant; \(T\) is the temperature; \(f_i J''\) is the Boltzmann fraction of the absorbing state, which has rotational quantum number \(J''\); \(B\) is the rotational overlap integral; \(A\) is the effective rate of spontaneous emission for all directly and indirectly populated states; \(Q\) is the total collisional quenching rate of the electronic excited state; and \(C_{\text{opt}}\) is the efficiency with which photons emitted from the gas are converted to photoelectrons in the ICCD camera. \(C_{\text{opt}}\) depends on the arrangement of the collection optics, spectral filtering, temporal gating, photocathode quantum efficiency, and intensifier gain. The term \(\frac{A}{A + Q}\) is known as the fluorescence yield, \(\phi\).

The PLIF signal, as defined in Eq. 1, has both explicit and implicit dependencies on temperature and pressure. Implicit temperature dependencies enter the signal equation through the Boltzmann fraction, the spectral overlap integral and the quenching rate. Pressure dependence is implicit in the overlap integral and the quenching rate. These terms are discussed in detail below.

The Boltzmann fraction, \(f_i J''\), expresses the population of rotational levels and is a function of temperature. It is given by:

\[
f_i J'' = (2 J'' + 1) \exp \left( -\frac{E_i J''}{kT} \right), \tag{2}
\]

where \(J''\) is the rotational quantum number of the lower rotational level and \(E_i\) is its energy. The spectral overlap integral, \(g_i\), determines the overlap between the laser spectrum and a particular transition. The parameter, \(g_i\), is the spectral profile of the laser; \(g_a\) is the absorption line shape, assumed to be a Voigt profile; \(v_i\) is the laser frequency; \(\Delta v_i\) is the laser linewidth; \(v_a\) is the laser frequency line; and \(\Delta v_a\) is the absorption linewidth. The functions \(g_i\) and \(g_a\) are normalised so that their individual integrals over all frequencies are unity. Shifts and broadening of transitions due to pressure and temperature are taken into account in the integral of the absorption lineshape.

The quenching rate depends on both pressure and temperature, as well as the species present in the flow:

\[
Q = \langle \sigma \rangle \left( \frac{P}{kT} \right) \tag{4}
\]

where \(\langle \sigma \rangle = \sqrt{8kT/(\pi m_{NO})}\) is the molecular mass of NO and the total electronic quenching cross-section is given by:

\[
\langle \sigma \rangle = \sum_p \chi_p \sqrt{1 + m_{NO}/m_p} \langle \sigma_p \rangle. \tag{5}
\]

The summation in Eq. 5 is over all perturbing species \(p\); \(\chi_p\), \(m_p\) and \(\langle \sigma_p \rangle\) are the mole-fraction, molecular mass and quenching cross-section of the perturbing species, respectively.

An understanding of the implicit temperature and pressures dependencies described by Eqs. 2 - 5 is important in developing a technique that is capable of instantaneous mole-fraction imaging with minimal temperature and pressure sensitivities.

\(\chi_{NO}\) imaging

In many applications of PLIF, a laser frequency that excites an isolated transition is chosen, ensuring that neighbouring transitions do not contribute to the PLIF signal. This simplifies quantitative analysis. However, to measure the mole-fraction directly, a strategy must be devised to minimise the temperature and pressure dependence of the signal. For example, by making some assumptions, simplifying the parameters in the signal equation and by exciting a particular transition with a weak temperature dependence, Clements achieved a fluorescence signal that was directly proportional to the mole-fraction of NO. However, the temperature range of his work (140-270 K) was far smaller than that required in our fuel-air mixing studies (190-700 K). Furthermore, the simplifying assumptions used in his work are not valid for the chemical environment produced in our facility. These restrictions have provided the current motivation to develop a technique suitable for a larger temperature range and the required chemical environment.

The aim of this work is to produce a fluorescence signal proportional to NO mole-fraction alone, that is, \(I_P \propto \chi_{NO}\). From Eq. 1, this can be satisfied if the term

\[
K = \frac{E_p}{A_{\text{abs}} kT} \sum_i [f_i J'' B g_i] \left( \frac{A}{A + Q} \right) C_{\text{opt}} \tag{6}
\]
is constant, independent of temperature and pressure.

For the purposes of calculation, it is assumed that the only variation in temperature is that due to the isobaric mixing of cold fuel with hot free-stream gases and that differential diffusion can be neglected. The temperature of the mixture is then calculated using an enthalpy balance:

\[
T_{\text{mix}} = \frac{\chi_{\text{fuel}} T_{\text{fuel}} + (1 - \chi_{\text{fuel}}) T_{\text{p, fuel}}}{\chi_{\text{fuel}} + (1 - \chi_{\text{fuel}})}
\]

The subscripts, \( \text{fuel} \), \( \infty \), and \( \text{mix} \) refer to the pure fuel stream, pure free stream, and a mixture of the two respectively; and \( \chi_T \) is the specific heat capacity. The heat capacity is a function of temperature, but is assumed to be constant in the determination of \( T_{\text{mix}} \). This is not expected to result in significant errors for the temperature range considered.

There are a number of variables available to adjust in order to achieve a constant value of \( K \): the operating conditions; the gas compositions; and the frequency and linewidth of the laser.

High-Reynolds conditions were chosen to achieve moderate total enthalpy and to be near-hypersonic while staying within the operating envelope of the shock tunnel. The free stream must be predominantly \( \text{N}_2 \) and the fuel mostly \( \text{H}_2 \) so that mixing can be analysed without the complication of combustion. A free stream Mach number of 4.8 was chosen for the purpose of studying mixing under hypersonic conditions for comparison with results obtained elsewhere under supersonic conditions. Combustion was inhibited by using a lower static temperature, a lower static pressure and a mostly \( \text{N}_2 \) free stream. The operating conditions of the fuel injector were chosen so that the fuel-jet static pressure equalled that of the free stream gas in the test section. The conditions are discussed in more detail below.

The amount of NO in the free stream was determined by the maximum tolerable absorption and the required quench rate. \( Q \). Absorption was limited to be less than \( 2\% \text{ cm}^{-1} \) to obtain relatively uniform illumination. This gives an upper bound to the amount of NO that can be present in the test section. If the amount of the quenching species is chosen such that \( Q > A \) (see Eqs. 4 and 6), this ensures that the implicit pressure dependence in the quenching cancels out the explicit pressure dependence of the PLIF signal. A trade-off must be made here, because a quenching rate that is too low will produce a signal that is low, while a quenching rate that is too low will cause the signal to have a large pressure dependence. The desired concentration of NO is produced by filling the shock tube with 98% \( \text{N}_2 \) and 2% \( \text{O}_2 \) by volume and allowing the shock heating in the tube to create NO by chemical reaction. Some NO reduction occurs in the expansion through the hypersonic nozzle.

It is also necessary to have the quench rate uniform throughout the flow. This means that the value of quenching is approximately the same for all values of \( T_{\text{mix}} \), so that the lifetime of the fluorescence in all regions of the image is the same. To address this problem, a trace amount of \( \text{CO}_2 \), which is non-toxic and a strong quencher, was added to the \( \text{H}_2 \). With \( \text{CO}_2 \) present in only trace amounts, the fluid mechanical behaviour of the fuel is indistinguishable from that of \( \text{H}_2 \).

Line Selection

The choice of laser excitation frequency is also very important in ensuring that variations in \( K \) are minimised. The Boltzmann fraction, \( f_{\nu^*} \), which appears in Eq. 6 for \( K \), is very different for low- and high-\( J \) lines. Low-\( J \) transitions are more highly populated at low temperatures, while high-\( J \) lines are more highly populated at high temperatures. By choosing the laser frequency to excite both low- and high-\( J \) transitions, the effective Boltzmann fraction can be fairly insensitive to variations in \( T_{\text{mix}} \). Thus, this will produce a value for \( K \) over a range of \( T_{\text{mix}} \) that exhibits lower variation than that produced by tuning to a single, isolated transition. Calculations were completed over the entire \( \text{A-X}(0,0) \) NO spectrum to find transitions that minimised variations in \( K \) while maximising signal. The optimal laser frequency was 44282.38 cm\(^{-1} \), centred on the \( ^2\Pi_{1/2}(27) \) transition. Once the excitation frequency is chosen, the absorption must be calculated again to check that it is still \(<2\% \text{ cm}^{-1}\). If this is the case, the only parameter left to adjust is the laser linewidth. The above calculations were repeated for the laser linewidths available and the we chose the linewidth that minimised the temperature sensitivity of the fluorescence signal.

Figure 1 shows the contributions to \( K \), from all the lines overlapped by the laser and the combined value of these, for increasing amounts of fuel. Though a number of absorption transitions contribute to the fluorescence signal, the dominant ones are the \( ^2\Pi_{1/2}(27), ^2\Pi_{3/2}(24) \) and \( ^2\Pi_{1/2}(8) \) transitions. These three transitions clearly show the effect of the Boltzmann fraction on the signal: the \( ^2\Pi_{1/2}(8) \) has a high signal for low temperatures, while the \( ^2\Pi_{1/2}(27) \) and \( ^2\Pi_{3/2}(24) \) transitions have a high signal for higher temperatures. When summed together these produce a reasonably constant \( K \) and thus a signal that is proportional to the mole-fraction of NO to within \( \pm 6.4\% \) over the specified temperature range.

**Fig. 1** Contribution of individual transitions to the total PLIF signal per mole of NO, \( K \) as defined by Eq. 6. \( K_{\text{max}} \) is the maximum total PLIF signal per mole of NO.

**PLIF** signal level variation for pressures of 5, 10, 20, 40 and 50 kPa is shown in Fig. 2. The signal decreases by about 40% in going from the 50 kPa case to the 5 kPa case, indicating that the PLIF signal is weakly dependent on pressure. To further reduce this pressure dependence the quench rate could be increased, at the cost of reduced signal and/or increased absorption.

The PLIF signal is shown in Fig. 2 to be a monotonic function of fuel mole-fraction at a given pressure. Therefore, the theoretical modelling can be used to convert experimental PLIF images to a quantitative measure of fuel mole-fraction under constant pressure conditions, or in regions where the pressure has a known value.

**Fig. 2** PLIF signal level variation with pressures of 5, 10, 20, 40, and 50 kPa. The PLIF signal \( S \) is normalised by the maximum signal \( S_{\text{max}} \) for the range under consideration.
Flow Conditions and Model

The experiments were performed using a free-piston shock tunnel. A conical nozzle with a 125 mm diameter exit and 35 mm diameter throat was used to produce the required flow Mach numbers. Free stream conditions with a static pressure of 40 kPa, a static temperature of 700 K and Mach number of 4.8 were produced. The $\text{N}_2/\text{O}_2$ test gas mixture produced approximately 1.6% NO, 1.2% $\text{O}_2$, 0.06% O, with a balance of $\text{N}_2$ by volume in the test section (calculated using the computer code STUBE\textsuperscript{21}). The injected fuel was at a pressure of 40 kPa and a temperature of 190 K, giving a Mach number of 1.7. The fuel gas contained 0.3% CO$_2$ with a balance of hydrogen.

The supersonic flow produced by the tunnel passes over a centrally-mounted plate into which each fuel injector is inserted. The fuel injectors used in this investigation are shown in Fig. 3. The fuel injector at the top of the figure is referred to as the plane-base fuel injector and is used as the datum injector. The other three fuel injectors are hypermixers. The first of these (b) is referred to as the castellated fuel injector because of its segmented blunt trailing edge.\textsuperscript{22} Such trailing edges have been shown to reduce drag by converting some of the spanwise vorticity into streamwise vorticity.\textsuperscript{3} The others are referred to as the (c) unswept compression-expansion ramp (UCER) and (d) swept compression-expansion ramp (SCER), fuel injectors respectively.

For the castellated fuel injector, streamwise vorticity is generated by pressure differences between the projection surfaces and recess regions. In the case of the ramp fuel injectors, the pressure differences on the compression and expansion surfaces produce streamwise vorticity. The resultant streamwise vorticity forms into pairs of counter-rotating vortices which entrain the injected fuel. This causes the fuel-air interface to stretch and therefore increases the mixing. The addition of sweep to the compression-expansion ramp increases the strength of the vorticity generated.

A schematic of the experimental arrangement is shown in Fig. 4. The operation of the shock tunnel is described by Stalker.\textsuperscript{23} Before firing the tunnel, the laser is tuned to a particular NO transition and pulsed at a fixed repetition rate. The recoil of the tunnel initiates an electronic trigger which stops the laser from continuously triggering and, with a preset delay, triggers the injection system. A transducer in the nozzle reservoir region registers the shock reflection from the end of the shock tube and the laser and camera systems are triggered 1.4 ms later. This delay corresponds to the time period during which the flow is steady in the test section.

Specific Flow Geometry

Figure 5 shows a schematic of the flow over a scramjet fuel injector, with a height of 8 mm, without fuel injection. The flow is uniform in the free stream, and expands around the base of the fuel injector on both upper and lower surfaces. At the base of the fuel injector a region of very hot, low-pressure separated flow forms. This low-speed recirculation region interacts with the high-speed inviscid region via the separated boundary layer which lies between them.

After its expansion over the base, a recompression shock forces the flow to move parallel to the free stream again. The flow between the recompression shocks is at approximately constant pressure, since pressure can be considered to be approximately constant across a slowly growing shear layer. A wake region, having properties similar to the boundary layer at separation at the injector edge,
is in the middle of the recompression shocks. The flow in the wake is hot and travelling slowly, while the flow between the wake and the recompression shocks is relatively cooler and faster. Therefore, the region between the recompression shocks has a uniform pressure but varying temperature, velocity and density.

When fuel is injected, the flow is qualitatively similar but the recompression shocks are further apart and the fuel-jet issues into the wake region.2

PLIF Excitation and Detection

Light from a Nd:YAG laser at a wavelength of 1064 nm passes through a frequency-doubling crystal producing 532 nm light which pumps a dye laser operated with a mix of Rhodamine 590 and 610 laser dyes. The dye laser outputs light at 574 nm which is frequency-doubled and then mixed with the residual 1064 nm light to produce UV light at 226 nm. This light excites transitions in the \( \text{A} ^2\Sigma^+ \rightarrow \text{X} ^2\Pi(0,0) \) band of NO. Part of the beam is split off and used to monitor the laser energy and for wavelength calibration by passing it through a flame; the LIF from the flame is imaged onto a spectrometer and detected by a photomultiplier tube. Each pulse of the laser usually produces about 3 mJ of energy. A low pressure, room temperature LIF spectrum of an isolated transition determines an upper limit to the linewidth of 0.9 ± 0.1 cm⁻¹. When injection-seeding the Nd:YAG laser, the laser linewidth is observed to be 0.5 ± 0.1 cm⁻¹.

To determine these laser linewidths, a portion of the original beam was split off using a beamsplitter and attenuated by a neutral density filter before passing through a test cell containing a small percentage of NO in an NO/N₂ mixture at low pressure, room temperature conditions. The laser was then scanned in frequency over an isolated absorption line of known line shape at these conditions. Scans were performed with low beam energies to avoid saturation effects and the laser linewidth was used as a free parameter to produce a best fit to the experimental scan.

The larger laser linewidth of 0.9 cm⁻¹ was used in the experiment to minimise pressure dependence through the overlap integral. That is, the larger laser linewidth ensured that the PLIF signal was less sensitive to absorption linewidth and pressure shift.

As described above, the laser frequency was selected by tuning to an absorption line in a flame. The conditions in this flame were typically at a pressure of 100 kPa and a temperature of about 1000 K. By comparison, the conditions in the mixing flowfield in the shock tunnel were typically at a pressure of 40 kPa and a temperature of about 700 K. Based on theoretical considerations, there is thus a pressure shift of approximately 0.043 cm⁻¹ in the flowfield with respect to the absorption line in the flame. This is negligible when compared with the laser linewidth and hence systematic errors due to this shift are considered insignificant.

The most significant error in selecting the laser frequency was due to the fact that the laser had to be tuned to a number of overlapping lines, rather than a single isolated line, in a sloping region of the spectrum. Our theoretical modelling indicated that the lowest temperature sensitivity would be achieved by tuning in a flame to a small broad peak on the wing of a larger sharper peak. The broadness of this feature, caused by the large number of overlapping lines, meant that significant uncertainty was associated with laser frequency selection. This uncertainty was worsened somewhat further by thermal drifts in laser frequency between the time of tuning and the firing of the shock tunnel. This was minimised by using the smaller laser linewidth (achieved by injection seeding) in the tuning process and completing the tuning of the laser as close as possible to the time of firing the tunnel (about a 5 minute wait between tuning and firing). Tuning in a room temperature test cell was not feasible because the intensity of the small peak was too low at room temperature conditions. The experimental uncertainty in the measured fuel mole-fraction resulting from the uncertainty of tuning the laser is high because we are attempting to tune to a rapidly sloping region in the spectral domain.

The UV light is formed into a sheet by expanding the laser beam in one transverse direction with a 400 mm focal length cylindrical lens and then collimating it in that direction with a 500 mm focal length spherical lens. This spherical lens also focuses the beam in the other transverse direction to a thickness of approximately 600 μm. The effect of this cylindrical-lens/spherical-lens combination is to produce a sheet of approximately constant width and slowly varying thickness. A mask before the test section decreased the width of the beam from approximately 95 mm to 85 mm.

The fluorescence was imaged normal to the direction of the laser sheet onto a thermo-electrically-cooled ICCD camera. A UG-5 Schott glass filter was used to spectrally filter the fluorescence to remove any elastic scatter. A dye cell was used to monitor the energy variation in the laser sheet profile which was captured on a CCD camera simultaneously with the PLIF image of the flow. This profile can be used later for correction of the image. However, we found that using this dye cell profile for correction introduced streaks into the images. More uniform images were obtained by correcting them with a region at the top of the image containing pure free stream fluid assumed to be uniform.

Results and Discussion

Figure 6a is a non-injection image for the plane-base fuel injector, which is shown by the grey mask at the left of the image. Flow is from left to right. All streamwise images have the laser sheet passing through the fuel injector nozzle centreline, parallel to the flow and perpendicular to the fuel injector strut. The laser sheet enters from the top of the image producing the shadow region beneath the fuel injectors.

Since no fuel is injected, all the flow features are due entirely to the free stream passing over the fuel injector. The expansion around the base of the fuel injector results in a drop in pressure and temperature and causes a decrease in PLIF signal level in this region as predicted by Fig. 2. Recompression shocks force the flow to again travel parallel to the free stream and can be seen quite clearly in the centre of the image. The increase in pressure and temperature across this shock causes the signal to increase. The large variation in signal level in each of these features indicates a pressure dependence in the signal which is greater than that expected from the analysis (see Fig. 2). We believe this is due to the assumption made when using \( T_{max} \) in calculations. It assumes that the only variation in temperature occurs when fuel and free stream gases mix. However, temperature changes also occur across shock waves and this is not taken into account in the analysis.

As discussed above, according to the fluid mechanical considerations, the pressure is approximately constant between the recompression shocks. The temperature is expected to vary considerably...
in this region. However, contrary to our original assumption, here the temperature effects are not the result of fuel and air mixing. Rather, the temperature variations are a result of variations in density through the shear layer. Nonetheless, the relatively uniform signal in this region provides evidence that our excitation method is insensitive to temperature. Outside the compression shocks, the signal level varies markedly due to the larger pressure and temperature changes. The region of validity of our PLIF model, then, is limited to the region between the recompression shocks.

The pressure dependence is larger than that expected from the analysis. This is because our modelling considers only pressure variations in the mixing flowfield, that is, in the region between the recompression shocks. Outside this region, pressure variations are accompanied by temperature variations that are unrelated to mixing. This modifies the quenching environment in a way that is different from that predicted for mixing. This means that, in the expansion fan generated at the shoulder of the injector, a quenching-dependent signal variation is observed even though the fuel mole-fraction there is zero. The only way to make the signal completely independent of pressure (irrespective of location in the flow) is to further increase the quenching rate by adding more oxygen, which is a good quencher, to the coflow. A consequence of adding oxygen is that the amount of NO formed during the shock reflection process is also increased. This increases the absorption, which is undesirable. Limits placed upon the tolerable amount of absorption is thus what has restricted the amount of quenching we could have in our experiments, and is the reason why a pressure dependence remains.

Figures 6b and 6c show streamwise fuel injection images for the plane-base and castellated fuel injectors. Injection of fuel into the flow causes the recompression shocks to be pushed further apart. The expansions around the injector can still be seen, but they are smaller due to the change in position of the recompression shocks.

The images in Fig. 6 have not been converted to fuel mole-fraction. However, the scale to the right of the fuel injection images indicates qualitatively the amount of fuel present at any point between the recompression shocks.

For both fuel injectors, the recirculation zone at the base of the fuel injectors entrains the fuel, spreading it over the entire base region. The fuel-jets then narrow while passing through the wake, before spreading out again. It is at this point that the two flow fields start to differ. The vertical spread in the fuel jet issuing from the plane-base fuel injector increases very slowly over a distance of ten base-heights. Evidence of large scale structures inclined at about 45° to the flow direction are apparent.

In contrast to this, the castellated fuel injector shows a much greater vertical spread in the fuel jet over the same distance and evidence of vortex-enhanced mixing from about four base-heights. After this point, there is an increasing interaction between the fuel and the free stream with the appearance of eddies which grow with distance downstream. At about five base-heights, the fuel jet appears to separate into two, most likely due to the interaction with streamwise vortices. The fuel concentration appears to decrease with downstream distance for both fuel injectors.

Both ramp fuel injectors also show entrainment of fuel near the base of the fuel injectors, as seen in Fig. 7 which shows the streamwise images for the UCER and SCER fuel injectors. After the separation of the two jets they appear to diverge. Between three and five base-heights for the SCER fuel injector the fuel concentration decreases, while for the UCER fuel injector the fuel concentration appears the same from near the base to the end of the imaging plane. At five base-heights the fuel concentration increases again. This feature is most likely caused by streamwise vortices generated by the injector geometry, moving the fuel in and out of the imaging plane.

The images of the streamwise planes, while highly useful, cannot provide a complete and unambiguous report of the flow field. For instance, movement of fuel in and out of the imaged plane could be incorrectly interpreted as resulting from more rapid mixing than actually exists in the flow. By obtaining spanwise PLIF images, it is possible to remedy this shortcoming and obtain a complete picture of the flow development and the progress in the mixing process.

Due to experimental constraints that limited the optical axis to an off-axis perspective (see Fig. 4b), the spanwise images are distorted and sometimes slightly rotated. In order to correct for this, an image of a rectilinear grid was taken before each experiment. The distortion and rotation of the grid was then corrected using image-processing software and the correction parameters recorded for later use, so that an identical correction could be applied to the corresponding fluorescence image. Cross-plane images at different stages of the image correction process are shown in Fig. 8 for the plane-base fuel injector at three base-heights. The original image is on the left. The result of the correction for distortion and rotation is shown in Fig. 8b. The final image on the right is the corrected image which has been enhanced using image processing software in order to see the flow features clearly. The spanwise images shown below in Figs. 9 and 10 have been contrast-enhanced for this purpose.

Figure 9 shows spanwise images for the plane-base and castellated fuel injectors acquired on successive tunnel runs. Flow is out of the page and the laser sheet enters the field of view from above. These images have not been converted to fuel mole-fraction. The fuel-jet issuing from the plane-base fuel injector does not spread much in a horizontal direction. It does contain eddy-like features at the periphery of the jet, the largest of which is approximately 15% of the initial width of the jet. The interfacial length between the fuel and the free stream does not increase as rapidly as for the castellated fuel injector.

The castellated fuel injector images show fuel spreading out across the base of the fuel injector, caused by the evolution of streamwise vortices. This set of four streamwise vortices at the outer edges of the twin fuel-jets are clearly visible on the left and right of Figs. 9e and f. These vortices appear to play a significant role in stretching the fuel-air interface at distances less than five base heights from the fuel injector but, further downstream, they dissipate leaving eddies to assume the dominant role in further fuel-air mixing. These eddies in the castellated fuel injector flow field are of similar size to those in the plane-base fuel injector flow field, and are present in similar numbers.

Figure 10 shows the spanwise images for the UCER and SCER fuel injectors. At one base-height the UCER fuel injector shows a greater fuel spread across the base of the fuel injector. In both flows, the two fuel-jets are quickly separated into four regions. This is
thought to be due to powerful streamwise vortices originating in the flow at the vertical downstream edges of the ramps. The vortices are still apparent at five base-heights. This indicates that the vortices produced by the ramp fuel injectors are stronger than those produced by the castellated fuel injector, which, by five base-heights have dissipated. In addition to this, the mixing for the ramp fuel injectors is seen to be more efficient than the castellated fuel injector. Unlike the vortices produced by the castellated fuel injector which affect only the periphery of the fuel-rich region, the UCER and SCER vortices appear to cause large intrusions of fuel-lean fluid into the centre of the fuel-rich region from either side. These intrusions cause the increase in the interfacial area by separating the fuel-rich regions into four distinct areas. By the time the flow reaches ten base-heights downstream the vortices appear to have dissipated.

When comparing the UCER fuel injector to the SCER fuel injector, it appears that the SCER fuel injector is slightly more effective at enhancing mixing. At each downstream position, the vortices produced by the SCER fuel injector are not as strong as those produced by the UCER fuel injector. The degree of mixing in the flow produced by the SCER injector appears to be slightly more advanced than that of the UCER injector at each position. Similarly, the interfacial area between fuel and free stream for the SCER fuel injector is not as great as that for the UCER fuel injector. In apparent contradiction of this inference, the fuel in Fig. 10d seems more dilute than in 10h, indicating that the UCER fuel injector has a better mixing performance at ten base-heights.

The image of Fig. 8b is shown converted to fuel mole-fraction in Fig. 11 for both an instantaneous and averaged PLIF image. These images have been converted using theoretical relations between PLIF signal level and mole-fraction such as those shown in Fig. 2. Using CFD calculations, the pressure is predicted for each fuel injector flow-field at each position downstream. This is then the pressure used to determine the theoretical relation between PLIF signal level and fuel mole-fraction and convert the images. Were we able to completely remove the pressure dependence, the use of CFD data in this way would be unnecessary. This is one motivation for further work to reduce the pressure sensitivity even further.

The corrected instantaneous image shown in Fig. 11a is useful for comparison with time-dependent CFD calculations. However to allow for future comparisons with time-averaged CFD calculations, the images are averaged by invoking symmetry and, for the plane-base fuel injector, also by averaging the results from each of the three nozzles on each fuel injector configuration such as the image seen in Fig. 11b. This averaging process relies on the assumption that the time-averaged flow associated with neighbouring nozzles for a particular fuel injector are identical. It was used in the current work in preference to averaging over a large number of experimental runs because of time constraints on the facility.
Fig. 12 Averaged PLIF images converted to mole-fraction for a)-d) the plane-base and e)-f) the castellated fuel injectors. The fuel scale is valid only between the recompression shock waves.

Uncertainty Analysis

To determine how accurately the fuel mole-fraction can be measured using this model, we have calculated the sensitivity to the uncertainty in the most important fluid mechanical and spectroscopic parameters. A normalised sensitivity parameter $e_i$ is defined in terms of a generalised fluid mechanical or spectroscopic parameter $\xi$ as:

$$e_i \approx \frac{\delta S_i}{S} / \frac{\delta \xi}{\xi}.$$  \hspace{1cm} (8)

The sensitivity $e_i$ gives a value that relates the uncertainty in the PLIF signal, $S$, to a given uncertainty in the parameter, $\xi$. A value of unity for $e_i$, for example, indicates that a 1% uncertainty in the parameter produces a 1% uncertainty in the signal level.

In our work, we have sought to design our experiment such that the fuel mole-fraction can be determined as a simple function of the fluorescence signal. Designating the fuel mole-fraction $X_{\text{fuel}}$ as the first generalised parameter $\xi_1$, we have sought to achieve the functional dependence

$$X_{\text{fuel}} = \xi_1 = \xi_1(S).$$  \hspace{1cm} (9)

However, although we have achieved strong sensitivity of $S$ to $X_{\text{fuel}}$, the signal still has a weak dependence on other parameters. That is,

$$X_{\text{fuel}} = \xi_1 = \xi_1(S, \xi_2, \ldots, \xi_n).$$  \hspace{1cm} (10)

Hence correction for the effects of these other parameters need to be considered. Uncertainties in the values of these parameters will contribute to the overall uncertainty of determining the fuel mole-fraction. These considerations lead to the following estimate of the relative uncertainty in the fuel mole-fraction:

$$\frac{\delta X_{\text{fuel}}}{X_{\text{fuel}}} = \frac{\delta \xi_1}{\xi_1} \approx \frac{1}{\epsilon_1} \sqrt{\left(\frac{\delta S}{S}\right)^2 + \sum_{i \neq 1} \left(\frac{\delta S_i}{S}\right)^2}.$$  \hspace{1cm} (11)

This analysis can be used to estimate the uncertainty in the fuel mole-fraction determined from the analysis of the PLIF images. We have used our modelling of the fluorescence to convert the PLIF images to images of fuel mole-fraction. This conversion works reasonably well for the region between the recompression shocks, but is unreliable outside that region. To estimate the uncertainty in determining $X_{\text{fuel}}$ in the region between the recompression shocks, we have determined the values of the sensitivities $e_i$ for the most important independent parameters for conditions where $X_{\text{fuel}} = 0.5$, $p = 40$ kPa, $T = 445$ K. These values are listed in Table 1. Because of the approximately linear relationship between $S$ and $X_{\text{fuel}}$ in the region between the recompression shocks, the value of $e_1$ in that region is very close to 1.0.

As seen from this table, at these conditions, the PLIF signal level
The PLIF signal was strongly dependent on the gas composition, laser excitation frequency and linewidth. We chose gases with sufficiently high quenching cross-section to achieve $Q \approx 10^4$, reducing the signal’s pressure dependence. However, this amount of quenching needs to be increased to further decrease the pressure dependence. The laser excitation frequency and linewidth were chosen to overlap a number of transitions with both low- and high-$J$ rotational numbers. This assisted in removing the temperature dependence of the signal. Optimising the parameters in the PLIF signal equation allowed us to produce a signal proportionality to fuel mole-fraction in regions of the flow dominated by mixing.

Experimental PLIF images in the mixing regions of plane-base, castellated, unswept compression-expansion ramp, and swept compression-expansion ramp fuel injectors were obtained in both streamwise and spanwise planes using the optimum laser frequency and other conditions specified by the theory. The streamwise images showed evidence of large scale structures and show that the signal is proportional to fuel mole-fraction and insensitive to temperature. However, the images did show pressure dependence with the expansion around the fuel injectors and the recompression shocks being clearly visible in the streamwise images. This pressure dependence was smaller for the plane-base and castellated fuel injectors than for the ramp fuel injectors, making the images of the former amenable to further analysis and conversion to fuel mole-fraction images.

Analysis of the spanwise images for the plane-base and castellated injectors allowed qualitative comparisons to be made of their relative mixing efficiencies.

Concluding Remarks

A theory for instantaneous PLIF imaging of fuel mole-fraction in a flow with pressure gradients and large temperature variations has been presented. The aim was to achieve PLIF signal level proportional to fuel mole-fraction, independent of temperature and pressure.

### References


