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COMPARISON OF HYPERMIXING INJECTORS USING A MIXTURE-FRACTION-SENSITIVE IMAGING TECHINIQUE

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ABSTRACT

Experiments which visualise the fuel mixture-fraction for different types of fuel injectors considered for use in supersonic combustors are described. The flowfields of two different fuel injectors are compared in a qualitative manner.

INTRODUCTION

Successful development of a supersonic combustion ramjet (SCRAMJET) engine depends critically on finding ways to mix fuel and air efficiently at supersonic flow conditions (Gutmark et al, 1995.). A planar laser-induced fluorescence (PLIF) method for visualising fuel mixture-fraction was developed by Fox et al (1998). This paper describes an application of that method to two different mixing flowfields.

EXPERIMENTAL METHOD

Flow conditions and model

The injectors used in this experiment are shown in figures 1 and 2. The injectors were mounted on the base of a strut which spanned the nozzle of the shock tunnel. The first of these (figure 1) has a segmented blunt trailing-edge and is termed the castellated injector. The other (figure 2) is referred to as the swept compression-expansion ramp (SCER) because of its trailing-edge configuration. These injectors are termed hypermixers and are designed to generate streamwise vorticity to enhance mixing by increasing the interfacial surface area and the magnitude of gradients between the fuel-air interfaces (Gaston et al, 1998).

The experiments were performed in the Australian National University's T3 free-piston shock tunnel (Stalker, 1972). Freestream conditions at a pressure of 40 kPa, a temperature of 700 K and Mach number of 4.8 were produced with a chemical composition of 1.6% NO, 1.2% O_2, 0.06% O, with a balance of N_2 in the test section. The fuel was injected at a pressure of 40 kPa and a temperature of 190 K, giving a Mach number of 1.7; its composition was 0.3% CO_2 with a balance of hydrogen.

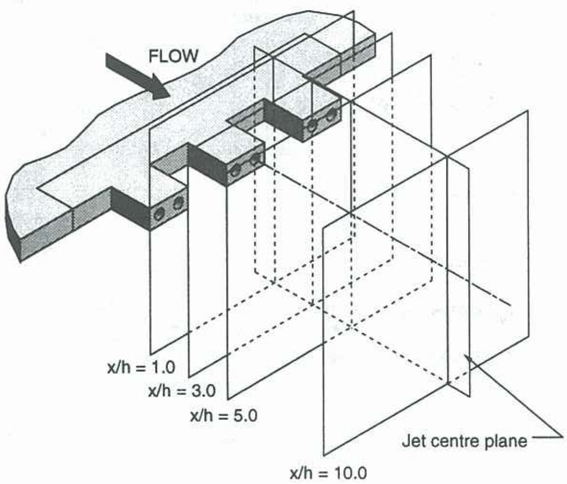

Figure 1: Schematic of the castellated injector showing the positions of the laser sheet used in the experiment.

PLIF Excitation and Detection

PLIF involves illuminating the flow with a thin sheet of laser light tuned to excite electronic transitions in a chemical species in the flow, in our case nitric oxide (NO). The fluorescence induced by this illumination is focussed onto an intensified charge-coupled device (ICCD) camera to produce an image of fluorescence intensity in that region (See figure (3)). By exciting two or more appropriate transitions simultaneously and satisfying certain constraints on the gas composition and the flow environment, the technique can yield signals that depend monotonically on fuel mixture-fraction (Fox et al, 1998). The laser sheet

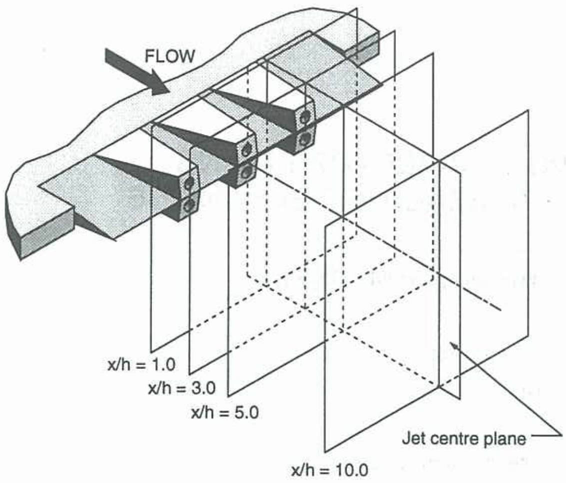

Figure 2: Schematic of the swept compression-expansion ramp (SCER) injector showing the positions of the laser sheet used in the experiment.

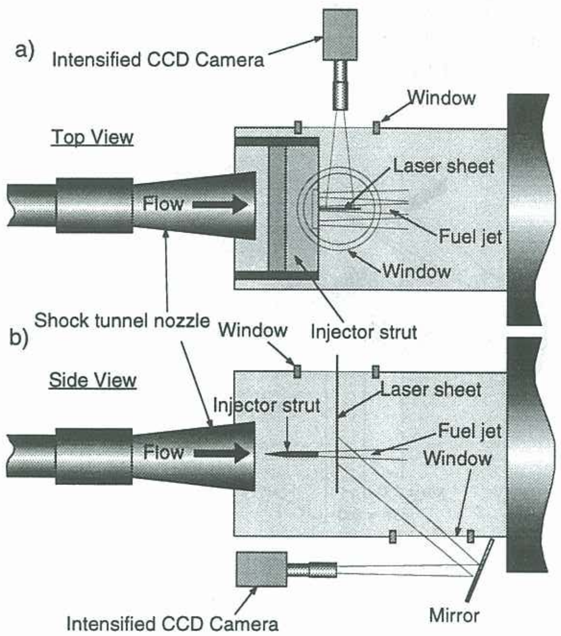

Figure 3: Schematic of experimental set-up a) for streamwise images and b) for cross-plane images.

sampled different planar cross-sections of the flow: (i) streamwise cross-sections, that are side views of the flow and are perpendicular to the injector, and (ii) crossplane images, that are parallel to the base of the injector. The crossplane images were taken at one, three, five and ten base-heights downstream of the injector; one base-height, h, is 8 mm.

RESULTS and DISCUSSION

Figure 4 shows instantaneous PLIF images for a) the castellated and b) the SCER injectors through the centre of the injector nozzles. The injector positions are shown by the grey masks to the left of the images. Flow is from left to right. The laser sheet enters from the top of the image, hence the shadow region beneath the injectors. Each image extends about 75 mm from the base of the injector. Expansions around the injectors can be seen, as can the recompression shocks which force the flow to travel parallel to the freestream again. These images have yet to be corrected to achieve a direct proportionality of signal intensity to mole-fraction of NO and thus a quantitative measure of mixing. The scale to the right of the images indicates the inverted signal: white indicates a high inverted signal, black indicates low inverted signal. The work by Fox et al (1998) shows that the signal has a pressure dependence. However in regions where variations in pressure are relatively small, such as between the recompression shocks, the signal is only very weakly dependent on temperature and is monatonically dependent on fuel mixture-fraction. Thus, in such regions, it is possible to obtain a qualitative image of the fuel mixture-fraction. There, white represents a high fraction of fuel and black represents a low fraction.

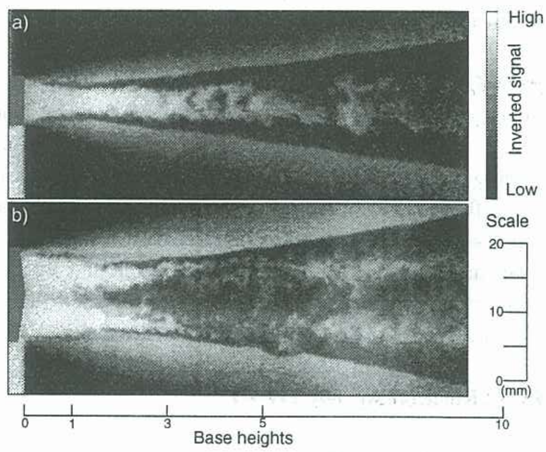

Figure 4: Instantaneous, streamwise mixture-fraction-sensitive PLIF images for a) the castellated and b) the swept compression-expansion ramp (SCER) injectors through the centre of the injection nozzles.

The image of the castellated injector indicates that the recirculation zones at the injector base entrains the fuel, spreading it over the whole base region. The fuel jet then narrows as it passes through the wake neck before spreading out again. After this point there is an increasing interaction between the fuel and freestream with the appearance of small eddies which grow with distance downstream. The fuel jet appears to separate into two beyond five base-heights. This bifurcation is most likely due to the interaction of streamwise vortices generated by the injector geometry. This is more easily seen in crossplane images shown later in figure 7. The concentration of fuel appears to decrease downstream of the injector. The SCER injector also shows fuel entrainment near the base of the injector. The fuel jets move away from the centre line in a vertical direction and between three and five base-heights, the fuel concentration decreases. These two features are most likely caused by streamwise vortices, generated by the injector geometry, lifting the fuel outside the imaging plane. After about five base-heights the fuel mixture-fraction in the image plane increases in concentration and spreads. At this point the fuel jet moves back into the imaging plane.

Figure (5) is a comparison between a) an average of four experimental streamwise PLIF images and b) a computational fluid dynamics (CFD) Reynolds-averaged image of mass-fraction for the castellated injector at the same flow conditions and position. The entrainment of the fuel at the base of the injector is also seen in the CFD image.

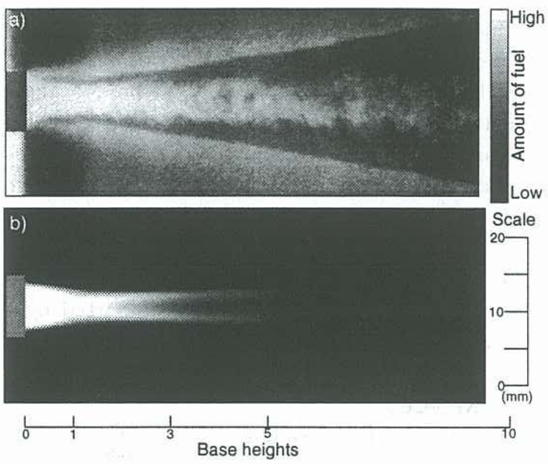

Figure 5: A comparison of a) an average of four experimental streamwise PLIF images and b) a CFD image, for the castellated injector.

Figure (6) shows a comparison between a) an average of four experimental streamwise PLIF images and b) a CFD Reynolds-averaged image of the SCER injector at the same flow conditions and position.

The above streamwise images are useful to obtain a general idea of what is occurring in the flowfield. However, the streamwise images do not show a true picture of the fuel jet charactistics as the vortical structures move the fuel in and out of the visualised region. This would lead to an inaccurate interpretation of the image. For this reason, crossplane images were obtained which reveal more of the 3D flow features.

Figure (7) shows crossplane images of the central injection port for a) - d) the castellated injector and

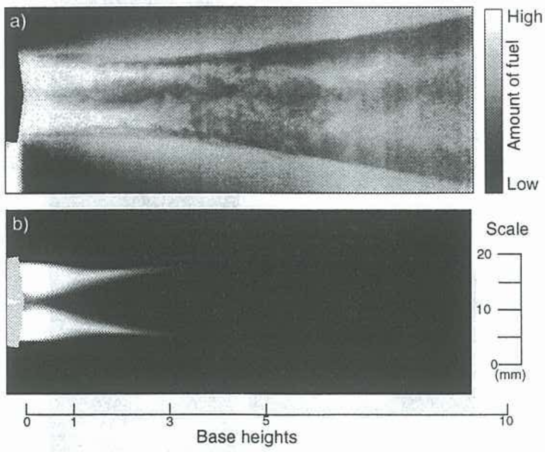

Figure 6: A comparison of a) an average of four experimental streamwise PLIF image and b) a CFD image, for the SCER injector.

e) - h) the SCER injector. From top to bottom is increasing distance downstream of the injector.

The flow is highly three-dimensional for both injectors. The castellated injector shows fuel spread across the base of the injector, caused by the production of streamwise vortices which are being formed within a few base-heights. These vortices, with a horse-shoe shape, are quite apparent at three base-heights and cause the entrainment of freestream fluid into the fuel region. However, the vortices for the castellated injector appear diffuse at five base-heights. At increasing distance downstream, the fuel jet appears to be decreasing in concentration and spreading outwards, but does not appear to fragment.

The SCER injector also shows fuel spread across the base of the injector and the production of vortices at one base-height. Unlike the castellated injector, the vortices are still apparent at five base-heights. This indicates that the vortices produced by the SCER injector are much stronger than the castellated injectors. At five base-heights the fuel is breaking up into four regions; this will help the mixing process by increasing the surface area of the fuel available for mixing. Similar to the castellated injector, the fuel jet appears to be decreasing in concentration and spreading outwards as it travels downstream.

Figure (8) shows a comparison between a) an experimental crossplane image of the castellated injector that has been averaged using flow symmetry, and b) a CFD image at the same conditions and position. The two images are in good agreement for the position and the shape of the fuel jet. However, the fuel jets in the CFD appear to be diverging more than those in the experimental image.

Figure (9) shows a comparison between a) an ex-

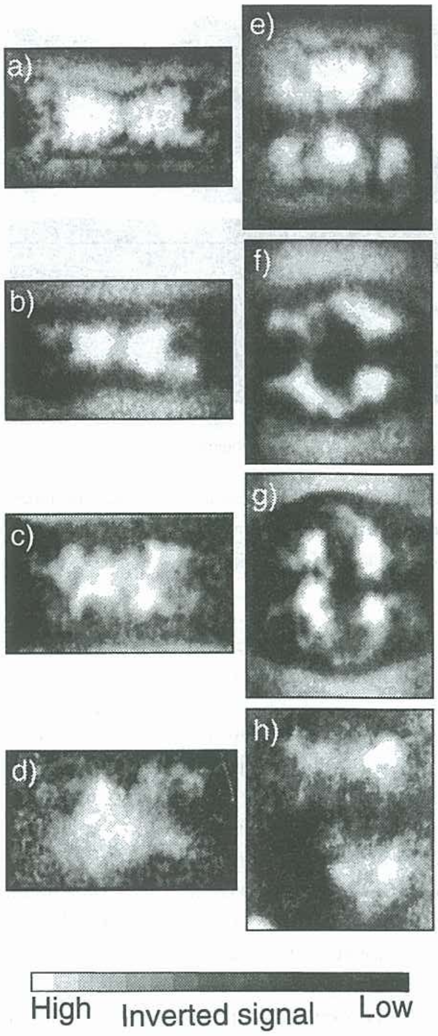

Figure 7: Crossplane images for a) - d) the castellated injector and e) - h) the SCER injector. From top to bottom is 1, 3, 5, and 10 base-heights downstream from the injector base.

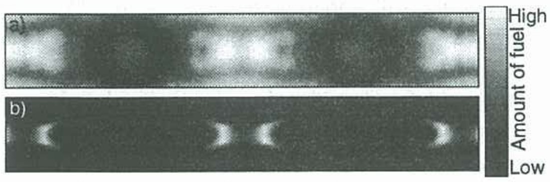

Figure 8: A comparison of a) a averaged crossplane image of the castellated injector, and b) a CFD image of the same flow. These images are taken at three base heights downstream from the injector base.

perimental crossplane image for the SCER injector that has been averaged using flow symmetry, and b) a CFD image at the same conditions and position. Again, the two images are in good agreement for the position and the shape of the fuel jet structures. In the vertical direction the fuel jets in the CFD appear

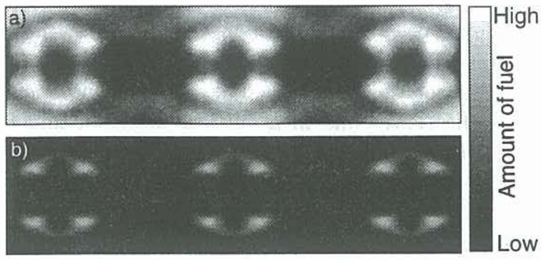

Figure 9: A comparison of a) a averaged crossplane image of the SCER injector, and b) a CFD image of the same flow. These images are taken at three base heights downstream from the injector base.

to be diverging more than those in the experimental image, however, the sideways spread of the fuel is slightly greater for the experimental image than the CFD.

CONCLUSIONS

A fluorescence technique to visualise fuel mixture-fraction has been applied to flowfields produced by two different fuel injectors. The technique allowed qualitative comparisons to be made of these fields for streamwise and spanwise cross-sections of the flow. The experimental PLIF images were also compared with theoretical maps of fuel mixture-fraction.

ACKNOWLEDGMENTS

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