Fuel Distribution Measurements in a Model Low NOx Double Annular Combustor using Laser Induced Fluorescence

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Abstract

Planar laser induced fluorescence (PLIF) was employed in a three sector, low NOx double annular combustor in order to characterise the combusting fuel spray. Naphthalene was employed as a fluorescent agent in odourless kerosene in order to determine the behavior of the light fractions in the fuel vapour, and the light to medium fractions in the fuel spray, while 2,5 di-phenyl oxizol (ppo) was employed to determine the behavior of the heavy fractions in the fuel spray. Counter-swirl air blast atomizing fuel injectors employing a nominal fuel spray included cone angle of 90 deg were employed to inject the kerosene fuel into the double annular combustor. Radial and axial measurements were performed on the combusting spray. Spatial variations in fuel spray placement were observed, together with radial anisotropy.

Introduction

Legislative controls on emissions from gas turbine combustors has prompted considerable technical innovation, both in the design of new combustors (intended to meet the decreasing emissions limits), and in the development of new combustion diagnostics. These new diagnostics aim to generate an increase in quantitative information and understanding of gas turbine combustion and the subsequent generation of emissions.

Gas turbine emissions such as soot, unburnt hydrocarbons (UHC), and carbon(II) oxide (CO) are a consequence of incomplete mixing of the fuel vapour and air in the combustion zone. For fuel spray combustion, this is a result of atomiser performance combined with the combustor aerodynamics.

Presently, there are no direct measurement techniques that combine measurement of atomiser performance with measurement of combustor aerodynamics in terms of being able to predict combustor emissions. The dynamical processes linking atomiser performance and combustor aerodynamics to combustor emissions are currently inferred from complex spray evaporation models coupled to cfd models using reduced flame chemistry. In turn, these models employ temperature, flow and combustor emission measurements as boundary conditions or calibration terms.

Current experimental techniques employed to measure atomiser performance include mechanical patternators [1], Phase Doppler Anemometry (PDA) and Laser Sheet Imaging (LSI) [2]. Mechanical patternators cannot, however, be used in a combusting system, as the liquid fuel is consumed. Phase Doppler Anemometry is used to measure pointwise mean and standard deviation drop size distribution, and mean and standard deviation droplet velocity distribution in low density sprays. PDA is unsuccessful, however, in measuring the drop size distribution in high density sprays. Laser Sheet Imaging is useful for the qualitative determination of fuel placement, spray isotropy, and spray cone angle, but exhibits a bias towards small drops in the spray field.

No diagnostic can currently measure or quantify the process of fuel spray evaporation. However, the spray cone angle, angle of spray dispersion, and spray penetration distance are indirect indicators of the process of fuel vapourisation. The spray cone angle and angle of spray dispersal also affects the combustion-acoustic coupling (rumble) in the combustor. 2psi - 3psi pressure oscillations in the combustor can cause rumble up to 200dB intensity.

Laser Induced Fluorescence (LIF) can be used to image a marker placed into the fuel stream. The concentration of this marker shows the distribution of fuel in its original chemical state and can be referred to as the Parent Fuel Fraction (PFF). Isothermal laser induced fluorescence in the quenched regime from a fluorescent marker mixed into a fuel is proportional to the number of excited fluorescent marker molecules. In turn, the number of excited fluorescent marker molecules is proportional to the total number of molecules in the meas-

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urement zone. In other words, the fluorescence emission from the measurement zone in the vapour phase is proportional to the local fuel vapour concentration.

This paper reports relative quantitative measurements of the liquid and vapour phase fuel distribution in a high pressure, three-sector low NOx double annular combustor using Planar Laser Induced Fluorescence (PLIF).

Experimental Method

1. The Double Annular Combustor

The three-sector double annular combustor was radially staged, with twin counterswirl airspray fuel injectors, and a splitter plate to separate the pilot zone from the main zone. High pressure fused silica windows were placed on both sides adjacent to the pilot zone to provide optical access perpendicular to the direction of flow. There was a further fused silica window at the rear of the rig, to provide optical access along the axis towards the injectors. A simple schematic of the side-view of the centre section of the double annular combustor is shown in Figure 1.

High pressure air for combustion mixing and for cooling was supplied from a large mass-flow central compressor. The combustor pressure was controlled through the use of a butterfly valve in the exhaust. The high pressure compressor air was supplied to an air heater, which heated the air to 530 K.

The combustor was operated at a ground idle condition (P = 3.0 bar, T(inlet air) = 530K, air flow rate = 0.95 $kg.s^{-1}$, and fuel flow rate = 3.8 $g.s^{-1}$ per injector), and a higher fuel flow rate condition of 4.9 $g.s^{-1}$ per injector to simulate take-off. Optical measurements were obtained in four planes (two radial planes and two axial planes) for the specified operating conditions.

2. Fuel Seeding

Exxol D80 odourless kerosene produces approximately 1/50 the fluorescence emission of conventional kerosene. Naphthalene (boiling pt ~ 220^{o}C) was employed as a fluorescent seed in order to determine the behaviour of the fuel vapour, and the light to medium fractions in the fuel spray. 2,5 Di-phenyl oxizol (ppo) (boiling pt ~ 350^{o}C) was employed in order to determine the behavior of the heavy fractions in the fuel spray.

The seeded fuel was prepared in a fuel drum. The fuel was pumped from the fuel drum to the combustor using a fuel pump with a recirculation system to maintain a stable fuel flow. Each time the fuel was changed, the fuel system had to be drained and cleaned to prevent contamination from the different seeds.

3. Optical Setup

A Lambda Physik EMG-150 MSC laser operating in narrow band tunable mode at 308nm was used for the fuel PLIF tests. The excimer laser produced laser pulses of 165mJ per pulse, of approximately 20ns duration. A collimated laser sheet was formed by passing the laser through a 1m spherical lens and a 1.67x cylindrical telescope. The first and second planes of measurement (radial measurements) required the laser sheet to be directed through the side window, parallel with the injector surface, spaced 5mm and 10mm away from the injector surface respectively. The laser sheet was 37mm in height, and approximately 0.15mm wide in the measurement region. The visible fluorescence was imaged through the rear window using a Princeton Instruments ICCD camera with a 50mm f1.2 Nikon lens.

The third and fourth planes of measurement (axial measurements) required the laser sheet to be directed through the exhaust window. A slowly diverging 2-d laser light sheet was formed by passing the laser through a 2m spherical lens and a slightly defocussed 1.67x cylindrical telescope. The laser sheet was 46mm in height, and approximately 0.25mm wide in the measurement region immediately downstream of the injector.

The third plane of measurement was centreline in relation to the centre fuel injector in the pilot zone. 200 single shot images were obtained for centre injector operation. The fourth plane of measurement was along the symmetry axis between the centre and port injector in the pilot zone, with both injectors operating at the conditions specified above.

Image processing

A data set of 200 single-shot images were collected for each condition. For the Parent Fuel Fraction (PFF) measurements the background was measured by imaging the system without the fluorescent marker present. The background signal was composed of several fixed quantities such as an image off-set imposed by the CCD camera and also varying quantities such as flame luminosity. The main contribution to the background was scattering from combustor surfaces.

The combined effects of variations in system gain and laser fluence across the measurement plane was removed by flatfielding the images with an image obtained from a constant concentration of acetone. A mean calibration image was obtained by averaging 20 single pulse images taken of a non-combusting uniform flow of acetone and air. Since the laser sheet profile varied slightly from pulse to pulse a small amount (~3%) of laser sheet detail was left in the processed images.

Passing the laser sheet through the spray caused some absorption in the laser sheet. This absorption was difficult to measure shot to shot. However, the mean absorption was estimated at approximately 10%. Therefore, the measurement error was estimated at approximately 12%.

After subtracting the background, the correction was made for spatial variation in the laser sheet and optical gain by dividing the data images by the laser flat-field images obtained from acetone fluorescence in the combustor.

Results and Discussion

1. Naphthalene Fluorescence

The imaging of the light fuel fractions using naphthalene was based on the measurements performed in an LPP mixing duct by Harding [3]. However, in Harding's work , the concentration of fuel in the liquid phase was very low in the region of measurement. This was not the case in the double annular combustor, where there was considerable overlap between liquid phase and vapour phase. Therefore the vapour phase fluorescence in the region of the fuel spray was subject to contamination by fluorescence from the liquid spray. Thus valid conclusions regarding the vapour state can be drawn only in regions where the fuel spray has fully evaporated.

Figure 2 shows a false colour image representing the mean naphthalene fluorescence image, obtained from two hundred images in the third plane defined above in the operating combustor for fuel flow rate 4.9 g/s. The mean spray cone angle was measured to be 79 deg ± 4 deg. A significant amount of fuel in the vapour state was observed to exist above the zone splitter, and near the roof of the combustor. This can be seen in Figure 2. This observation suggests that the kerosene spray was able to wet the roof and the zone splitter. This is a cause for concern, as fuel vapour evaporating off of the roof and the zone splitter may be transported into the burned gas without combustion, causing elevated UHC and soot emissions from the combustor. Elevated levels of UHC and soot emissions were indeed observed in the exhaust gas obtained from the double annular combustor.

In order to use naphthalene seeded odourless kerosene fluorescence as a quantitative marker of vapour state fuel distribution, simultaneous Mie scattering imaging of the spray field must be performed. This will enable the generation of a spray field mask to mask the liquid state region from the vapour state region in the measurements zone.

2. PPO Fluorescence

Figure 3 shows a false colour image representing the mean PPO fluorescence image, obtained from 200 single shot images in the third plane defined above for fuel flow rate 4.9 g/s. The mean spray cone angle was measured to be 110 deg ± 4 deg, which was significantly larger than that measured from the naphthalene fluorescence.

Figures 4 and 5 show false colour images representing the mean PPO fluorescence images obtained from 200 single shot images in planes 1 and 2 respectively, for fuel flow rate 4.9 g/s. Figure 6 shows a false colour image representing the mean PPO fluorescence image obtained from 200 single shot images, in plane 2, for fuel flow rate 3.8 g/s.

The ratio obtained by dividing the mean fluorescence intensity obtained from image 5 by the mean fluorescence intensity obtained from image 6 is 1.29 ± 0.14. This ratio provides a consistency check, and indicates that the PPO fluorescence has represented the heavy components in the fuel successfully.

Figures 4, 5 and 6 show that the liquid fuel distribution obtained from the air blast atomisers employed in this model low NOx combustor is anisotropic , with a 60% bias towards the port side (left side) of the injector relative to the starboard side (right side). When the ratio image ((1.29 x image 6)/image 5) is obtained, it demonstrates that the fuel distribution becomes more isotropic with an increase in fuel flow rate.

Conclusion

This work has lead to the following conclusions:

1. The heavy components in the fuel spray were measured to develop a spray cone angle of 109 deg ± 4 deg, while the light components were measured to develop a spray cone angle of 79 deg ± 4 deg.
2. Fuel vapour was observed adjacent to the roof and the zone splitter. It is suggested that this would lead to elevated UHC and soot emissions from this type of combustor. This has been observed.
3. PPO fluorescence has accurately represented the heavy components of fuel concentration.
4. The spray obtained from these airblast atomisers is anisotropic, producing a 60% port side bias relative to the starboard side.

5. The isotropy of the fuel spray obtained from these air blast atomisers has improved with increasing fuel flow rate.

References

[1] Lefebvre, A.W., *Gas Turbine Combustion*, 2nd Edition, McGraw-Hill, 1999, pp243 – 250.
[2] eds. K. Kohse-Hoinghaus and J. Jeffries, *Applied Combustion Diagnostics*, Taylor and Francis, 2002, Chapter 15.
[3] S. Harding, PhD Thesis, Cranfield University, Cranfield, Bedfordshire, UK (1997).

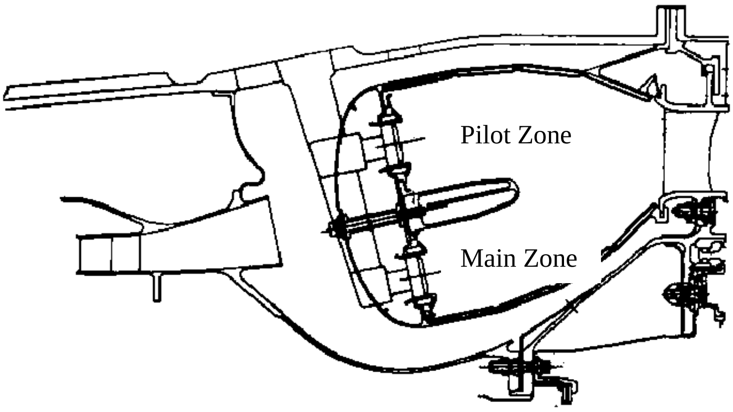

Figure 1. Side View of the Centre Section of the Double Annular Combustor

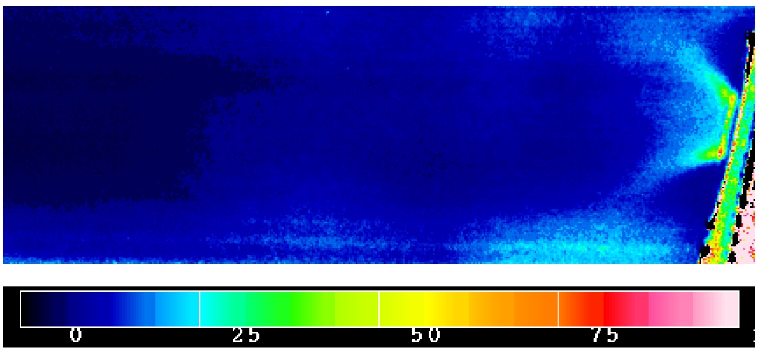

Figure 2. False Colour Image of Mean Naphthalene Fluorescence, obtained from Plane 3 in the Double Annular Combustor

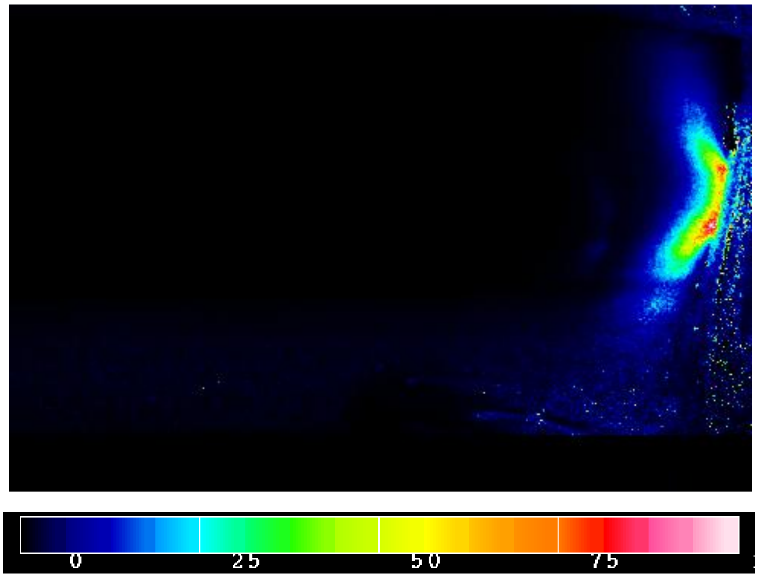

Figure 3. False Colour Image of Mean PPO Fluorescence, obtained from Plane 3 in the Double Annular Combustor.

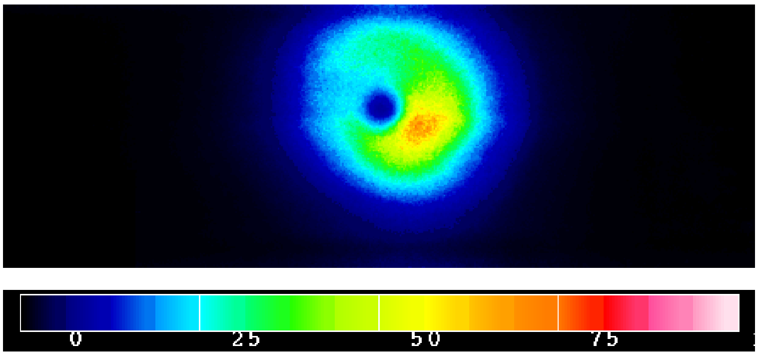

Figure 4. False Colour Image of Mean PPO Fluorescence, obtained from Plane 1 of the Double Annular Combustor

(Fuel flow rate = 4.9 g/s).

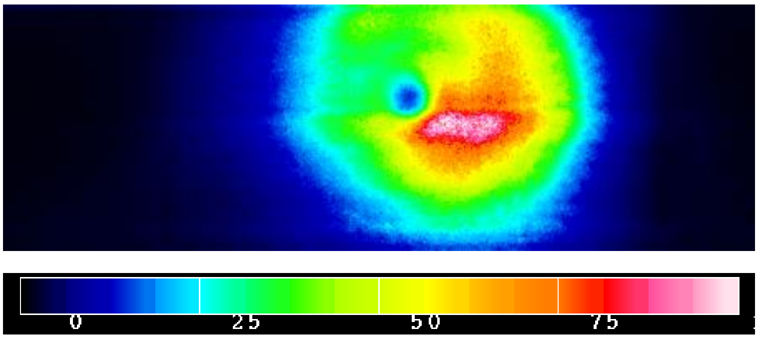

Figure 5. False Colour Image of Mean PPO Fluorescence, obtained from Plane 2 of the Double Annular Combustor.

(Fuel flow rate = 4.9 g/s).

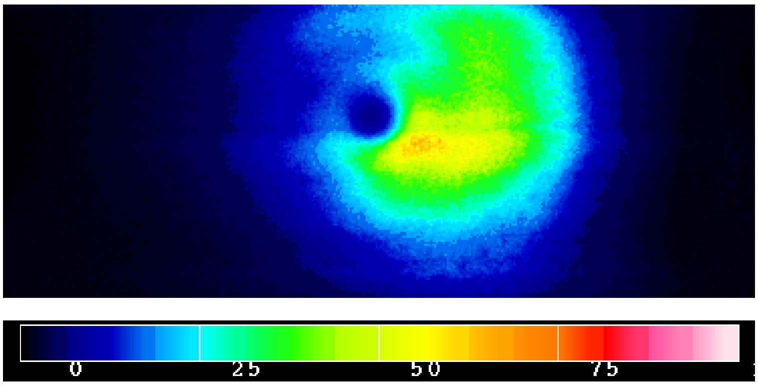

Figure 6. False Colour Image of Mean PPO Fluorescence, obtained from Plane 2 of the Double Annular Combustor.

(Fuel flow rate = 3.8 g/s).