THE RESPONSE OF FUEL INJECTOR SPRAYS TO ACOUSTIC FORCING

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ABSTRACT

Under certain conditions in gas turbine combustors, interaction with the fuel/air mixing process amplifies acoustic waves to an amplitude which may damage the combustor.

The fuel injector has an important role in this interaction. In this paper the role of the injector is studied with planar laser induced fluorescence (LIF) and Mie imaging and Laser Sheet Dropsizing (LSD), calibrated to yield AFR and SMD. The tests are non-combusting and low cost. The injector is run in a rig at up to 7 bar with scaled operating conditions such that the spray structure is representative of that in the engine. An acoustic perturbation is imposed on the airflow.

A transfer function describing the strength and phase of the response of AFR and SMD to the acoustic perturbation is extracted. Both AFR and SMD exhibit fluctuations which are coherent with the imposed acoustic oscillation. Comparison of the transfer functions to the results of combustion tests suggest that the spray measurements can predict which injectors are likely to encourage strong instability in the combustor.

INTRODUCTION

Lean combustion is being actively pursued as a means of reducing NOx emission from gas turbine combustors. However lean combustors can suffer from thermo-acoustic instability. Fluctuations in pressure lead to fluctuations in heat release, which in turn lead to fluctuations in pressure forming a feedback loop. If the mechanism that coupled pressure and heat release is such that the feedback is positive, the pressure fluctuations are amplified (the Rayleigh criterion). High pressure amplitudes may produce unacceptable noise and increases in vibration and heat transfer that shorten the life of the combustor.

Potential feedback mechanisms include vortex generation, Karlowitz stretch effects, acoustic modes of the combustion chamber, entropy waves, and injector effects. This paper explores the potential of injector effects as feedback mechanisms in kerosene fuelled aero gas turbine combustors.

Fluctuations in pressure at the injector may cause fluctuations in droplet size, AFR, fuel flow rate and air flow rate. Any of these can affect the heat release rate.

It is known that changing the injector can cause the amplitude of the pressure oscillations to increase or decrease, and even to cure the problem. The implication is that the design of the injector has an effect on the strength of feedback.

To study the effect of pressure fluctuations on fuel injector sprays we constructed a high pressure optically accessed sprays rig with a siren to modulate the airflow through the injector. The AFR and droplet size of the sprays were measured as a function of time using planar Laser Induced Fluorescence (LIF) and Mie scatter imaging techniques. The strength of response of a set of injectors, designed for the same combustor, but which in combustion tests produced dramatically different pressure amplitudes, were compared.

METHOD

The Cranfield Sprays Rig (Fig. 1) is an optically accessed chamber which allows gas turbine liquid fuel injectors to be operated at up to 7 bar (709kPa), 200^{o}C and 2kgs^{-1} air flow. 7 bar is sufficient to reproduce the spray pattern of any combustor pressure by using scaling procedures to find operating conditions that produce the same values for key flow descriptors (e.g. Re, We, Ma, Stk, air/fuel momentum ratio) in the rig and in the engine [1]. The resulting non-combusting intermediate pressure spray tests give detailed information on injector behaviour yet are significantly cheaper than combustion tests.

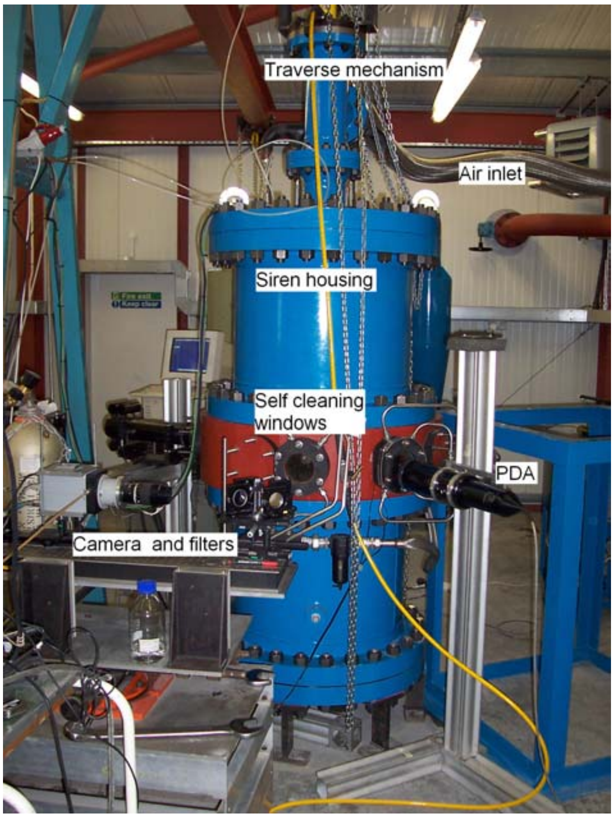

Figure 1 Cranfield 7 bar sprays rig

The rig windows are air-purged for clear optical access. The rig is fitted with a siren which modulates the air flow through the injector at frequencies of up to 500Hz [2]. The spray is not ignited.

The rig is instrumented with a Phase Doppler anemometer and laser sheet imaging equipment.

A plane in the spray is illuminated with a light sheet 50mm high and 1mm thick from a Lambda Physik CompEx110 excimer laser at 248nm wavelength and 100mJ pulse energy.

Light scattered by the spray is collected by a Princeton Instruments intensified CCD camera fitted with a 105mm Nikkor ultraviolet lens. A four-mirror system projects two images side by side on the CCD chip: one filtered to collect only Mie scattering and the other filtered to collect only fluorescence.

In the LIF image, pixel intensity is proportional to liquid volume fraction. The LIF and Mie images are ratioed to yield an image in which intensity is proportional to droplet SMD [3]. Using a stream of monodisperse droplets of known size the LIF image is calibrated to yield AFR values, and the LIF/Mie ratio image is calibrated to yield SMD in microns.

The fuel in Exxsol D-80 with m-terphenyl added as a fluorescent tracer.

The camera and laser were fired at a given delay after a timing mark on the siren. Images were taken every 22.5^o in the siren cycle. At each phase 200 images were taken: 100 with the light sheet propagating in one direction and 100 with the light sheet in the opposite direction. Each set of 100 were averaged and the attenuation of the light sheet as it passes through the spray corrected according to the method of Talley et al. [4].

The measurements were repeated with the siren at 12, 100 and 200Hz.

Five airblast injectors were measured. These were all designed for the same combustor and the same operating cycle. However in combustion tests in an engine, each injector produced a different pressure fluctuation amplitude, from zero to 9,000 Pa.

The operating conditions in the combustor tests at which the pressure fluctuation was measured was 317kPa abs, 380K, 7.62-11.00 AFR at the injector depending on the injector. These conditions were scaled to preserve the air velocity through the injector (which affects the acoustic impedance) and the patternation or spatial distribution of the droplets by preserving the air/fuel momentum flux ratio. Of the set of scaling rules described in [1] this rule gives the best possible match to the engine Re, Ma (which determine the air flow pattern) and Stk (which determines how closely the droplets follow the air flow pattern).

The scaled operating conditions used in the rig were 2.49kPa abs, 316K, 7.66-11.05 AFR, 6.18gs^{-1} fuel flow.

RESULTS

Fig. 2 shows a sequence of AFR images for injector B at 200Hz, and Fig. 3 the corresponding SMD images.

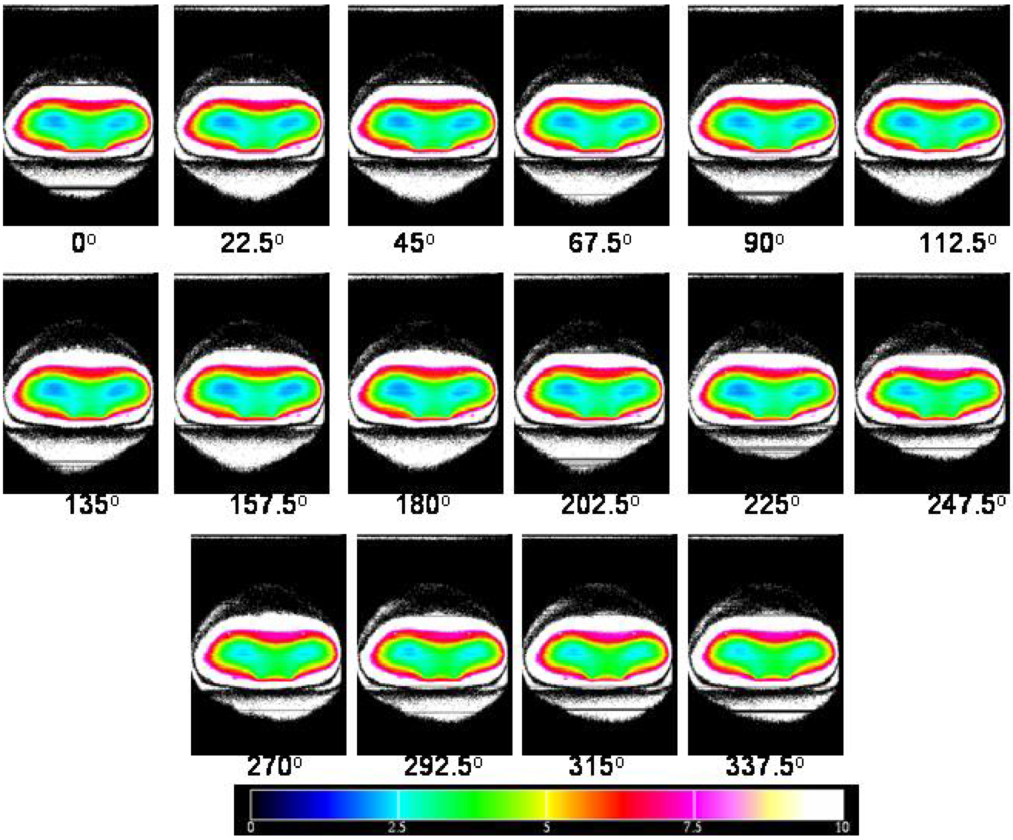

Figure 2 Sequence of AFR images at 200Hz

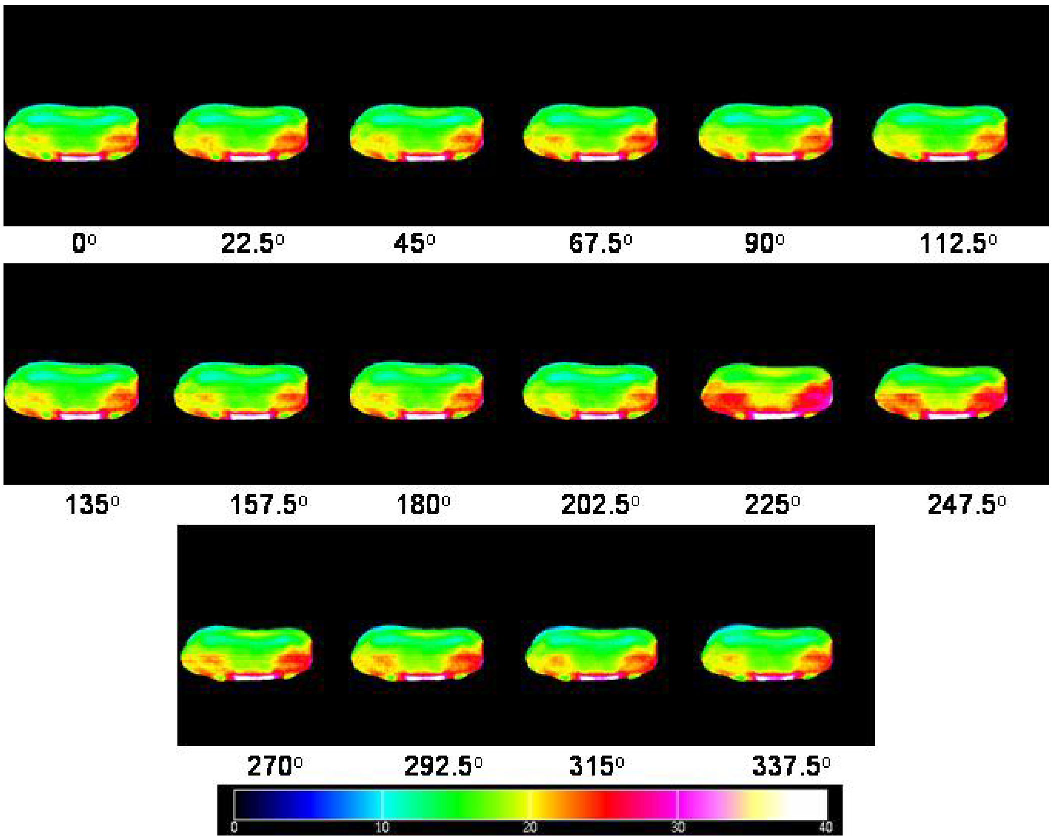

Figure 3 Sequence of SMD images at 200Hz

These images are processed to extract a transfer function The transfer function describes the relationship between the pressure fluctuation and the fluctuation in spray properties and takes the form shown in Eq. 1

$$Y = \overline{Y} + \widetilde{P}A\sin(\omega t + \phi) \tag{1}$$

Y is the spray property, either AFR or SMD in microns, at the particular point in the spray, at time t. $\widetilde{Y}$ is the fluctuating and $\overline{Y}$ is the mean value of Y, $\widetilde{P}$ is the fluctuating component of the airbox pressure in Pa, A is the amplitude or coupling constant in AFR/Pa or microns/Pa, θ the phase of the siren in the AFR or SMD/phase relationship ω is the air perturbation frequency and ϕ the phase lag of the peak in Y with respect to the peak in air pressure.

The values of AFR and SMD as a function of time are extracted from the processed images at four different positions in the spray, marked in Fig. 4.

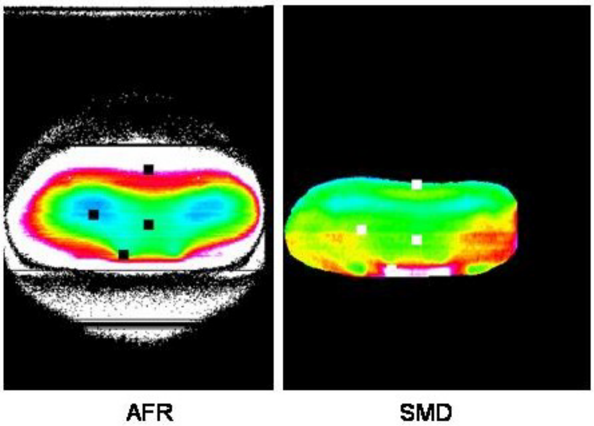

Figure 4 Positions in spray for which the transfer function is extracted.

Since the siren waveform contains harmonics, the time-histories of AFR and SMD for these points are first filtered to remove components at the harmonic frequencies.

A sinusoidal transfer function is fitted to the filtered time history. A factor relating to quality of fit is calculated. This is R^2/AC^2 which is the sum of deviations squared over the AC amplitude squared. Where the fit is poor, for example if the AC component is noisy or poorly sinusoidal, this value is large. This indicates the fluctuations are not coherent with and perhaps not due to the siren perturbation.

Table 1 shows the transfer function values for all five injectors, for the point at the centre of the recirculation zone.

Values of $A/\widetilde{Y}$ and R^2/AC^2 for the five injectors are shown in Table 2. $A/\overline{Y}$ is the ratio of the amplitude of the fluctuating component (per unit pressure amplitude) of AFR or SMD to the DC component and is summed over all three frequencies and over the AFR and SMD. Also shown are the pressure amplitudes observed in combustion tests with the same injectors

DISCUSSION

Both AFR and SMD show siren-driven fluctuations. These are both potential candidates for the feedback mechanism necessary to sustain combustion oscillation since the SMD affects the rate of release of fuel as vapour.

There is no detectable oscillation in cone angle at the pressure amplitudes used in these tests.

The phase is the same in every region i.e. the same phase holds throughout the spray- this is not surprising as the acoustic wavelengths are several times larger than the extent of the spray.

For a given region, the phase of the AFR and SMD fluctuations is different, typically by 140-220^o difference between the phase lags of SMD and AFR. A peak in air pressure will produce a peak in AFR and a trough in SMD as the air velocity and hence shear force peaks. The phase lag varies from injector to injector.

The amplitude of the fluctuations is greatest near the prefilmer exit, less on the centreline of the spray or in the recirculation zone.

The values of A are frequency sensitive- tending to be greater at 200Hz than 12Hz. In other words there is more fluctuation in AFR or SMD per unit amplitude of air oscillation at the higher frequencies. The injector may have a natural frequency at which it responds most strongly to air pressure fluctuations, and this may influence the frequency of combustion oscillation. However, when fitted to the engine, the natural frequency of the combustion chamber, and flow and mixing field effects, will also have a strong effect on the frequency of combustion oscillation.

There are some poor fits, as indicated by the values of R^2/AC^2, indicating that the fluctuations seen are not coherent with the siren, and may be unrelated to the siren. Poor fits are particularly common for injector E, which exhibited the weakest instability in combustion tests.

Table 1: Transfer function values for centre of recirculation zone

A	Y-bar (DC amplitude.)	A (AC amp. /Pressure amp.)	Phase (ϕ)	A/Y-bar	R^2/AC^2
AFR, 12Hz	3.17	1.66E-05	191	5.22E-06	2.42
AFR, 100Hz	4.09	5.92E-05	358	1.45E-05	10.82
AFR, 200Hz	3.83	8.69E-05	433	2.27E-05	5.64
SMD, 12Hz	19.89	1.34E-04	341	6.73E-06	2.44
SMD, 100Hz	15.51	1.74E-04	193	1.12E-05	15.81
SMD, 200Hz	15.61	2.53E-04	638	1.62E-05	4.62
B					
AFR, 12Hz	2.68	9.94E-06	406	3.71E-06	3.35
AFR, 100Hz	2.79	2.05E-05	433	7.36E-06	2.58
AFR, 200Hz	2.46	1.03E-04	428	4.17E-05	2.35
SMD, 12Hz	20.37	7.40E-05	196	3.63E-06	1.35
SMD, 100Hz	20.43	1.74E-04	263	8.50E-06	4.99
SMD, 200Hz	21.48	7.11E-04	483	3.31E-05	4.05
C					
AFR, 12Hz	4.31	3.31E-05	401	7.68E-06	0.41
AFR, 100Hz	4.78	2.60E-05	318	5.43E-06	4.89
AFR, 200Hz	4.64	5.61E-05	513	1.21E-05	4.07
SMD, 12Hz	17.06	9.87E-05	151	5.79E-06	0.95
SMD, 100Hz	14.35	1.74E-04	118	1.21E-05	1.28
SMD, 200Hz	15.23	1.42E-04	628	9.34E-06	4.51
D					
AFR, 12Hz	2.86	7.46E-06	321	2.61E-06	2.45
AFR, 100Hz	2.90	2.60E-05	303	8.97E-06	1.21
AFR, 200Hz	4.33	1.04E-04	483	2.41E-05	1.37
SMD, 12Hz	27.18	1.41E-04	101	5.19E-06	0.14
SMD, 100Hz	27.32	3.95E-04	133	1.44E-05	1.25
SMD, 200Hz	18.53	2.53E-04	313	1.36E-05	3.49
E					
AFR, 12Hz	3.29	1.90E-05	136	5.79E-06	7.87
AFR, 100Hz	3.62	4.46E-05	388	1.23E-05	12.40
AFR, 200Hz	3.23	7.11E-06	378	2.20E-06	118.49
SMD, 12Hz	18.61	1.23E-04	276	6.63E-06	2.82
SMD, 100Hz	16.62	1.58E-04	238	9.50E-06	15.50
SMD, 200Hz	19.39	5.85E-04	553	3.01E-05	2.74

Table 2: Correlation of transfer function amplitudes and fit quality with combustion instability amplitudes

		A/Y-bar summed over all freqs, both SMD and AFR			R^2/AC^2 summed over all freqs, both SMD and AFR		
Injector	Instability amplitude/Pa	Centre of recirc. zone	Near prefilmer exit	Centreline at recirc. zone height	Centre of recirc. zone	Near prefilmer exit	Centreline at recirc. zone height
A	9235.3	7.65E-05	9.55E-05	7.00E-05	41.7	22.4	52.4
B	8270.4	9.80E-05	1.00E-04	1.13E-04	18.7	30.0	15.2
C	8270.4	5.24E-05	6.54E-05	4.06E-05	16.1	22.5	28.7
D	1378.4	6.89E-05	1.14E-04	4.54E-05	9.9	20.6	29.1
E	344.6	6.66E-05	6.23E-05	5.42E-05	159.8	95.4	57.1

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Table 2 shows the relation between transfer function values and the pressure amplitudes measured in combustion tests. R^2/AC^2, the fit quality function, is high when the fit of the sinusoidal transfer function to the measured data is poor. The correlation between transfer function amplitude and combustion pressure amplitude is not perfect, as the test excludes several combustion related processes that contribute to combustion instability. However $A/\overline{Y}$ is consistently high for the injector with strongest instability, (A) indicating a strong coherent response to the siren, and the fit quality parameter is consistently high for the injector with lowest instability amplitude (E) due to it's non-sinusoidal, non-coherent response to the siren.

This suggests that low cost spray tests of this type can be used identify those injectors most and least likely to encourage instability before any expensive combustion test.

The sprays test reveals injector-related instability feedback mechanisms but does not include combustion, combustor walls, or combustor and flowfield related mechanisms such as combustion chamber natural frequency, stretch factor and vortex shedding effects. However the prediction of the best and worst injector is promising and suggests that the relatively inexpensive non-combusting test used here may be used to test a selection of injectors and select those that are least likely to amplify combustion instability, before any (order of magnitude more expensive) combustion test is carried out.

CONCLUSIONS

The response of the spray field of five gas turbine airblast atomisers to acoustic perturbation has been measured. Both AFR and droplet size have been measured quantitatively with optical imaging techniques. The measurements were made in a sprays rig which can reproduce spray behaviour representative of the engine but at significantly lower cost.

The non-combusting method used here excludes several combustion and combustor design related phenomena but allows us to study the injectors role in instability in isolation.

Both AFR and SMD show siren-driven fluctuations. These are both potential candidates for the feedback mechanism necessary to sustain combustion oscillation since the SMD affects the rate of release of fuel as vapour

There is a correlation between the transfer function amplitude measured in the non-combusting spray test, and the pressure amplitude observed in combustion tests. The correlation is not perfect, as the spray test excludes several combustion related processes that contribute to combustion instability. However the ratio of the AC to the DC component of the measured spray transfer functions is consistently high for the injector with strongest combustion instability, indicating a strong coherent response to the siren, and the fit quality parameter is consistently high for the injector with lowest instability amplitude due to its non-sinusoidal, non-coherent response to the siren.

The prediction of the best and worst injector is promising and suggests that the relatively inexpensive non-combusting test used here may be used to test a selection of injectors and select those that are least likely to amplify combustion instability, before any (order of magnitude more expensive) combustion test is carried out.

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NOMENCLATURE

AFR	Air/fuel ratio (dimensionless)	SMD	Sauter Mean Diameter (microns)
Ma	Mach number (dimensionless)	Stk	Stokes' number (dimensionless)
Re	Reynolds' number (dimensionless)	We	Weber number (dimensionless)

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