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MEASUREMENT AND ANALYSIS OF THERMOACOUSTIC OSCILLATIONS IN A SIMPLE DUMP COMBUSTOR

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A study of the spectral characteristics of the temperature, pressure, heat release and velocity fluctuations associated with combustion oscillations has been carried out in a laboratory dump combustor burning premixed butane and air. The interactions between the different fluctuating variables have been measured. The trends in the relative phases of these parameters and their implication for the driving mechanism and the modelling of thermoacoustic instability are assessed.

1. INTRODUCTION

The drive towards "lean burn" operating conditions for dry low-emission combustion systems has resulted in an increased incidence of thermoacoustic oscillations often leading to problems of flame extinction and structural vibration. The instabilities arise from unsteady heat release in the system which couples with pressure fluctuations in the combustion chamber, usually at a frequency associated with a longitudinal or bulk acoustic mode of the combustion system. In contrast to the high-frequency transverse acoustic modes which traditionally arise in rocket motors, the low-frequency longitudinal oscillations are difficult to suppress using traditional control techniques. Therefore, there has been renewed research effort in recent years to improve the understanding of the driving mechanisms behind the instabilities in order to develop more effective modelling and control strategies.

The phase relationships between the various fluctuating parameters in a combustion system have long been known to be of critical importance in the generation of combustion oscillations. Lord Rayleigh [1] noted that the generation of thermoacoustic oscillations in a duct was dependent on the relative phase between the heat transfer and the pressure osscillations, with the acoustic oscillation being amplified when the heat release and pressure waves were in phase and the oscillation being damped when they were out of phase. Lang and Vortmeyer [2] monitored the pressure and the heat release in a laboratory combustor and confirmed the applicability of the criterion to combustion. Thus, identification of the source of the unsteady heat release in various combustor configurations is a key issue if modelling and control strategies are to be developed. Particular attention has been focused on coherent structures in the flow as the

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driving mechanism for combustion instabilities, as discussed by Schadow and Gutmark [3]. Poinsot *et al.* [4] have identified large-scale coherent structures in the flow in a number of different combustor geometries, whilst Schadow *et al.* [5] have suggested the burning of vortices as they convect downstream as the probable source of unsteady heat release. In a study using a model afterburner, Langhorne [6] observed that this convection behaviour extended only a short distance from the flameholder with acoustic propagation dominating the region further downstream.

In addition to experimental analysis, modelling techniques for thermoacoustic interactions have been proposed by a number of authors. Dowling [7] used an idealized model of combustion to compare techniques to calculate the thermoacoustic frequencies and subsequently developed a non-linear model for the thermoacoustic oscillations [8]. This assumed that the non-linearity is in the heat release and predictions were found to be very close to those associated with harmonic fluctuations. Bloxsidge *et al.* [9] performed a number of forcing experiments in which the phase relationships between various fluctuating parameters in a model afterburner were investigated to establish an empirical model. Changes in the flowfield were found to affect the generated sound indirectly through interaction with the heat release rate by Hedge *et al.* [10] and they highlighted the importance of the effect of the coupling between the flowfield and the heat release on the resulting pressure fluctuations indicating that feedback was an important element of any model.

Measurements of the fluctuating temperature, pressure, heat release and velocity and the interactions between these variables have been obtained for a laboratory dump combustor. The combustor geometry, characterized by a step expansion into the combustion chamber, was chosen as this type of combustor has been shown to exhibit unsteady combustion over a wide range of operating conditions as reported, for example, by Sivasegaram and Whitelaw [1 1]. Two thermoacoustic models are applied to the system to assess their ability to predict the behaviour observed in the experimental rig.

2. EXPERIMENTAL CONFIGURATION AND INSTRUMENTATION

A simple, small-scale, two-dimensional premixed dump combustor, a schematic of which is shown in Figure 1, was used for the investigation. The combustion chamber was formed from 44 mm × 44 mm steel-box section with 3 mm wall thickness. The overall downstream length was 1·175 m, with the open downstream end exhausting to atmosphere. The inlet plane (dump) was formed by two rearward facing steps with an expansion ratio at the dump plane of 1 : 8·8. The high blockage ratio at the steps ensured that acoustic resonances were uninfluenced by upstream geometry and that acoustic frequencies corresponded to the quarter-wave mode in the downstream duct, with a pressure antinode at the dump plane and a pressure node at the exhaust. Butane was supplied from a pressurized gas cylinder whilst a compressed air line provided a constant air supply. Both lines had variable pressure regulators with simple gate valves to control the flow rates of gas and air

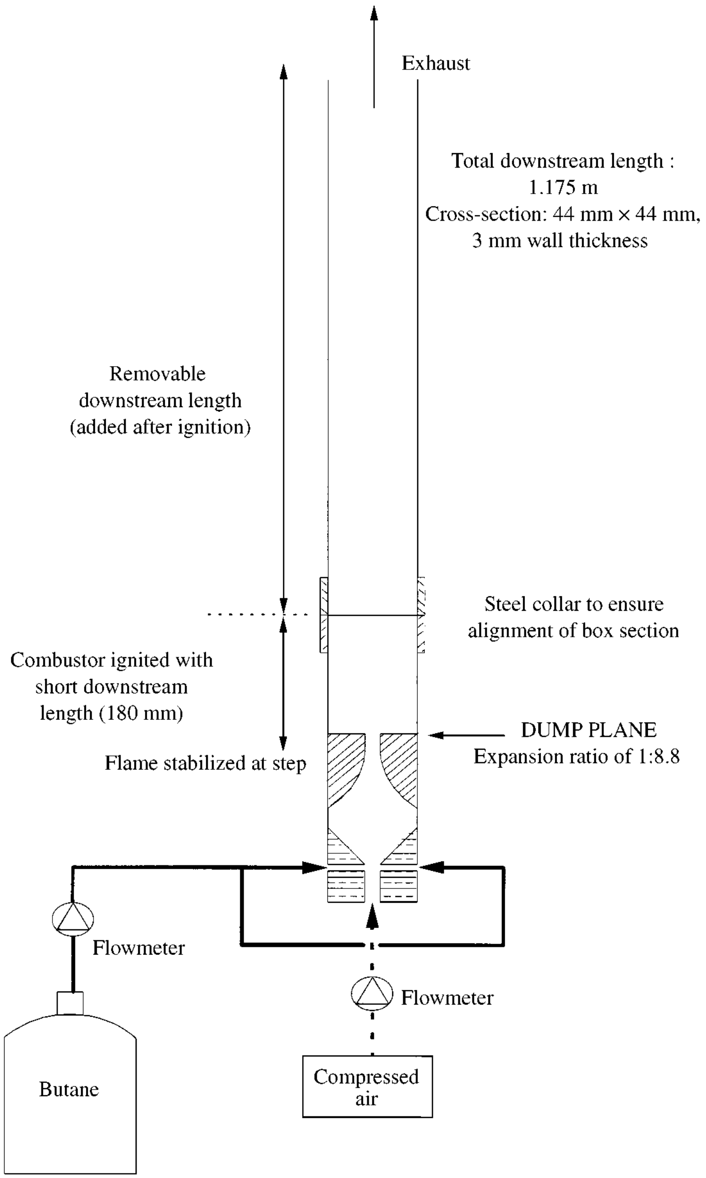


Figure 1. Schematic diagram of experimental configuration.

which were monitored using variable area flowmeters. The butane and air were mixed a short distance upstream of the rearward facing steps in a conical expansion arrangement.

Fluctuating wall pressure was measured using a probe microphone (Bruel and Kjaer, type 4170) which was water cooled. The cooling system had a semi-infinite end condition in order to minimize the distortion effects on the pressure wave. The probe microphone with cooling system was calibrated against a $\frac{1}{2}''$ microphone in order to quantify the distortion effects introduced into the measured wall pressure signal. Type R 0·002″ unsheathed Pt/13% Rh–Pt thermocouples were used to measure fluctuating temperature in the combustor. The leads were threaded through twin-bore alumina tubing (2 mm outside diameter, 0·5 mm bore) and the arrangement clamped in a split bolt. Access to the combustion chamber for pressure and temperature measurements was provided by suitably drilled and tapped holes in the combustor wall.

Optical access to the combustion chamber was provided by two circular sapphire windows, 12·5 mm in diameter. C_2 radical emission was monitored using a photo-multiplier and narrowband optical filter (515 nm, 10 nm bandwidth). Hurle *et al.* [12] showed the emission intensity from free radical in the flame to be linearly proportional to the heat release. Fluctuating velocities in the combustion chamber were measured by a single-component laser Doppler anemometry system, using TS1 32 mW HeNe laser in forward scatter mode. TiO_2 particles of 0·25 μm nominal diameter were used as seeding particles.

3. DATA ACQUISITION AND SIGNAL PROCESSING

Autospectra were used to show the periodic nature of the fluctuating parameters, while their interactions were quantified using coherence functions (frequency domain normalized cross covariance) and phase. Temperature, C_2 radical emission and pressure measurements were recorded on a Hewlett Packard 35660A spectrum analyzer, thus enabling the direct recording of autospectra and the coherence and phase between the measurements. Measurements of the acoustic pressure were corrected for the bias effects introduced by the microphone cooling system and of temperature for the thermal inertia of the thermocouple.

The laser doppler anemometry (LDA) receiving optics were connected to a TS1 1980b counter processor which was interfaced to a Pentium-type PC. The LDA velocity data was acquired in the usual way from the counter of validated data and time between data points. For the simultaneous measurement of fluctuating velocity and pressure, the microphone was sampled by an A to D board (Amplicon PC-30PGL), which was interfaced to the same Pentium-type PC. Validated LDA data points were used to trigger the A to D acquisition system and both signals were subsequently reconstructed as detailed by Scholten *et al.* [13]. The data were corrected for the low-pass filter effect [14] and auto- and cross-spectra were obtained using MATLAB-based spectral analysis software.

4. RESULTS AND DISCUSSION

Large-amplitude pressure oscillations were generated in the combustor over the entire flammability range and flammability limits found to agree well with those observed by Sivasegaram and Whitelaw [11]. An equivalence ratio of 0·9 was found to correspond to the generation of a very strong pressure oscillation at the quarter-wave resonant frequency of the combustion chamber for a range of inlet velocities and the results for spectra with an inlet velocity of 10·2 m/s at this equivalence ratio are presented. The auto-spectra for the various measurements are outlined and coherence is used to identify those frequencies where the phase measurements are meaningful. The phase relationships between pressure and temperature and pressure and velocity are then presented for a range of velocities and equivalence ratios.

4.1. AUTOSPECTRA AND COHERENCE

A typical wall-pressure auto-spectrum measured 220 mm downstream from the dump plane is shown in Figure 2(a). The spectrum shows a very high-amplitude peak ($>$ 160 dB) at the acoustic resonant frequency (144 Hz), with harmonics of the fundamental mode also clear in the plot. Of particular interest is the fact that both even and odd harmonics are obvious in the plots whereas, from linear acoustic theory, only resonances corresponding to odd harmonics only should arise. The presence of even harmonics in the pressure auto-spectrum indicates that a corresponding heat release must exist at these frequencies so that the combustion instability is strongly non-linear.

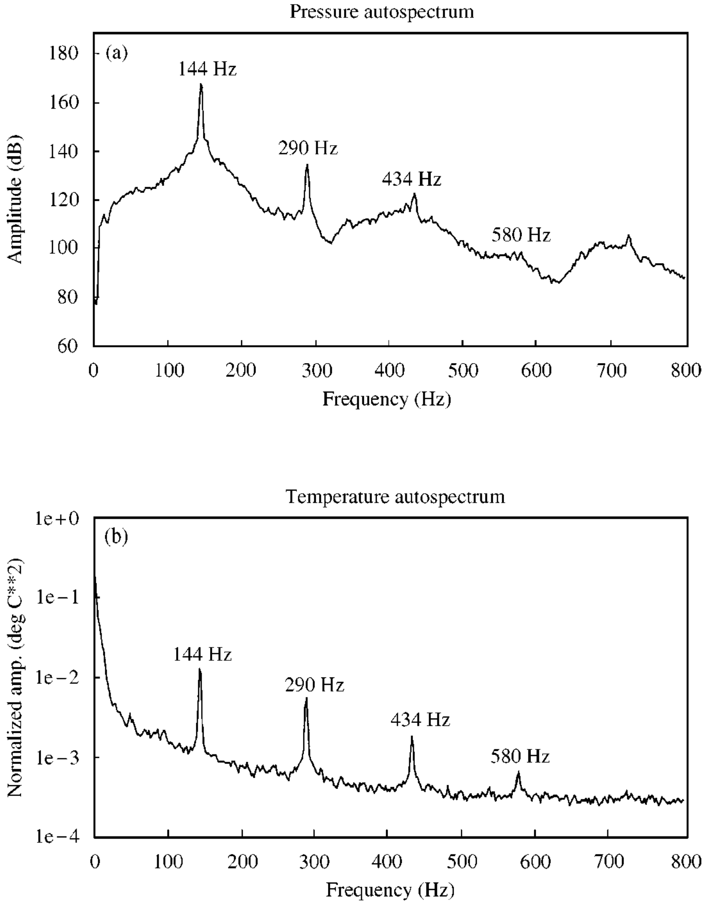
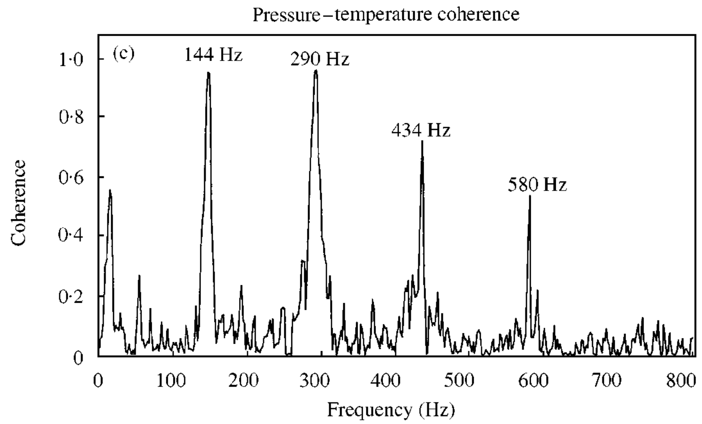
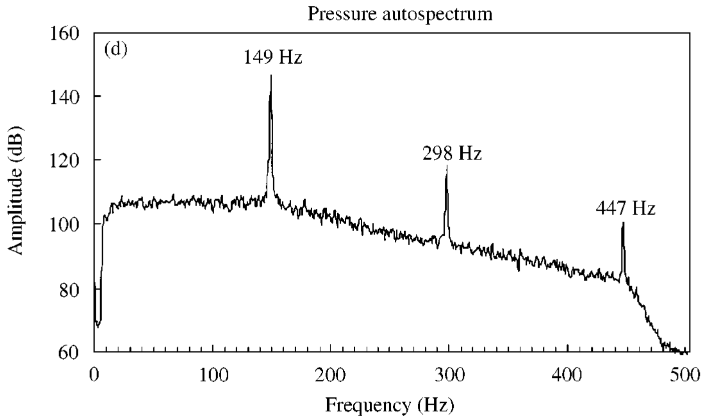


Figure 2. Auto-spectra and coherence of pressure. Temperature and velocity.





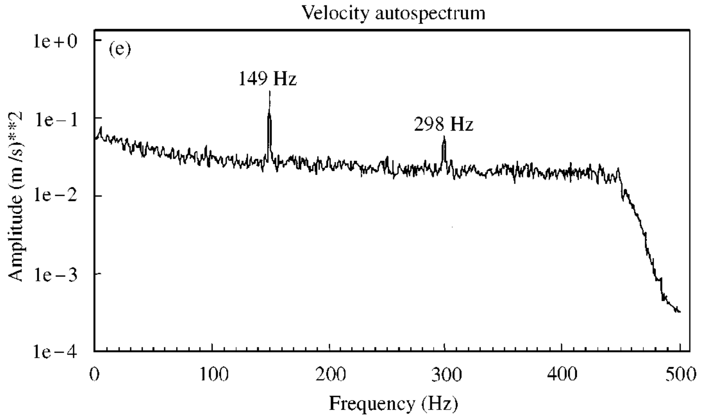


Figure 2. Continued

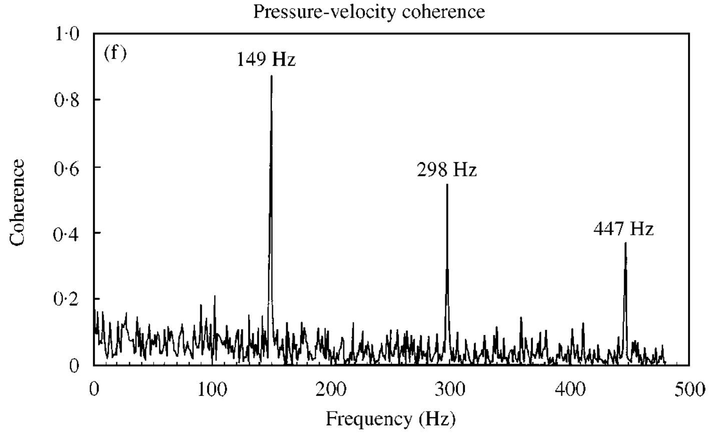


Figure 2. Continued

Temperature auto-spectra calculated from measurements obtained 50 mm downstream from the dump plane also exhibited peaks at both odd and even harmonics as shown, for example, in Figure 2(b). (This data has been normalized as the amplitude has not been corrected for the loss-pass filter effect.) The coherence between temperature and pressure is seen from Figure 2(c) to be practically unity at the quarter-wave frequency with high values at the harmonics indicating very strong coupling at these frequencies. Apart from the resonant frequency and its harmonics, the coherence was practically zero so that there is no correlation between the variables at these frequencies. The coherence measurements between the C_2 radical emission measurements and the pressure were also found to exhibit strong peaks at the acoustic resonant frequency and its harmonics. Although the C_2 measurements were badly contaminated by mains noise from the photomultiplier, it was possible to establish, from a limited series of measurements, that the temperature and C_2 measurements were highly correlated and in phase.

To establish the pressure–velocity interactions, the pressure data was acquired at the same time as velocity using a trigger from the LDA counter to sample the pressure. As the mean sample rate from the counter was 2500 Hz, the spectra have been estimated up to 500 Hz to minimize the step noise induced by sample and hold signal reconstruction. Figure 2(d) shows the pressure spectrum with the first three harmonics clearly evident in the spectrum. (The peak of 150 dB at 149 Hz is at a lower amplitude than that at 144 Hz for the pressure/temperature analysis.) Figure 2(e) shows a velocity auto-spectrum measured 50 mm downstream from the step expansion at the midpoint of the cross-section and peaks at the quarter wave resonant frequency and the first harmonic are evident. Although these spectra have been corrected for the low-pass filter effect associated with the signal reconstruction scheme, the broadband noise or "step noise" associated with LDA measurements is evident in the results. The coherence between velocity and wall pressure (Figure 2(f)) indicates strong interaction at the quarter-wave frequency with peaks at the first and second harmonic also visible, even though the latter is submerged in the step noise in the calculated spectrum.

4.2. PHASE

To examine the interaction mechanisms between pressure and temperature (and by inference, pressure and heat release) and pressure and turbulence, phase measurements for a range of operating conditions were obtained from cross-spectra at those frequencies where high coherences were observed. Bloxsidge *et al.* [9] modelled the feedback coupling between the pressure fluctuations and the heat release rate using a Strouhal number (St) given by

$$\mathrm{St} = fr/u,$$

where f is the resonant frequency, u is the propagation velocity and r is the radius of the flameholder.

Figure 3 shows the relative phase between temperature and wall pressure in the current experimental configuration, plotted as a function of this Strouhal number using half the dump plane height as the length parameter. A linear relationship can be seen to exist between the relative phase and the Strouhal number for different flow rates and equivalence ratios. The phase between C_2 radical emission and pressure was found to be similar to the temperature/pressure measurements so that fluctuations in temperature and heat release can be considered to be convecting downstream with the bulk flow. The phase can be seen to be unaffected by variations in equivalence ratio, with all the data collapsing onto a single curve. Thus, very similar behaviour to that observed by Bloxsidge *et al.* [9] exists in the current experimental configuration. The convection of temperature fluctuations at a constant velocity was observed by Schadow *et al.* [15], who suggested that the temperature fluctuations are generated at the acoustic frequency during the combustion process and release heat periodically while being convected downstream.

The phase relationship between velocity and wall pressure was investigated using measurements obtained at inlet velocities of 5·1, 10·2 and 12·7 m/s, with the fluctuating velocity measured at four different positions downstream from the dump plane (25, 50, 75 and 100 mm) and the pressure. Figure 4 shows the phase as a function of Strouhal number evaluated as fl/u where l is the position of the velocity measurement relative to the dump plane. It is clear that the phase between

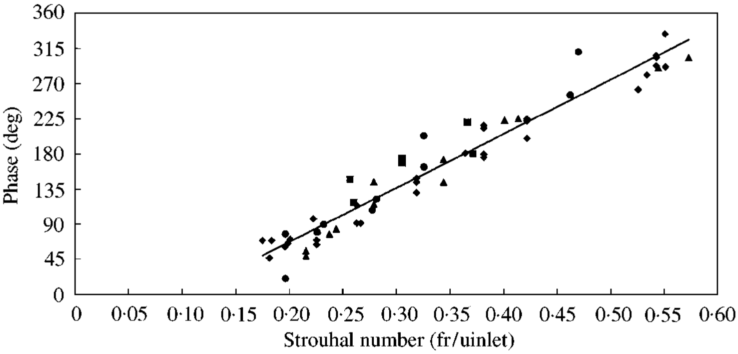


Figure 3. Phase for temperature and pressure. ◆ phi = 0·9; ● Phi = 0·8; ▲ phi = 1·0; ■ phi = 1·1.

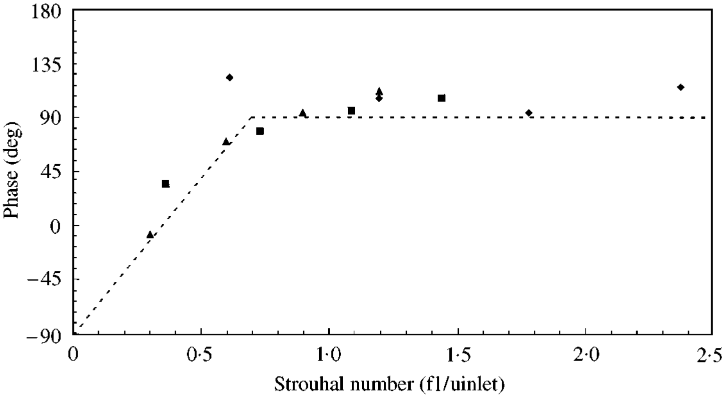


Figure 4. Phase for velocity and pressure. ◆ $u = 5{\cdot}1$ m/s; ■ $u = 10{\cdot}2$ m/s; ▲ $u = 12{\cdot}7$ m/s.

fluctuating velocity and wall pressure is quite different to that between temperature and pressure in that there are two distinct regimes. At low Strouhal numbers (i.e., close to the dump plane), the phase increases linearly with Stouhal number from − 90° at the dump plane in a similar fashion to the temperature/pressure results. For higher Strouhal numbers, the phase is approximately constant at about 90°. In the immediate downstream region, the velocity fluctuations resulting from vortex-shedding convect downstream through the burning region. Through this region, as the vortices burn and dissipate, the pressure/velocity interactions are dominated by this convection. Further downstream, the pressure/velocity interactions are dominated by the acoustics of the system. These results are similar to those obtained by Langhorne [6], who observed convective behaviour a short distance downstream from the flameholder with the phase of the C_2 radical emission (heat release) assuming an almost constant value close to that of the pressure further downstream. Thus, it seems that the unsteady sources originate in near flame region where convective behaviour dominates the interactions whereas outside this region, acoustic propagation is the principal mode of interaction.

4.3. THERMOACOUSTIC MODELLING

Two thermoacoustic models incorporating feedback between the flowfield and the heat release were applied to the configuration tested in this work. The first, proposed by Dowling [7], assumed the flame was an infinitely thin sheet at the dump plane and that heat release due to feedback coupling was directly proportional to the mass flow rate. The second, from Bloxsidge [9], modified the feedback to ensure that the phase relationship between the heat release and other parameters was as observed in experiments.

A comparison of predicted frequencies with the measure frequency for a range of inlet velocities is shown in Figure 5. The model assuming that heat release is directly proportional to the mass flow rate results in values being underpredicted by some 10%. The Bloxsidge feedback model provides a good estimate of the frequency although the predictions closest to the measured frequency are from

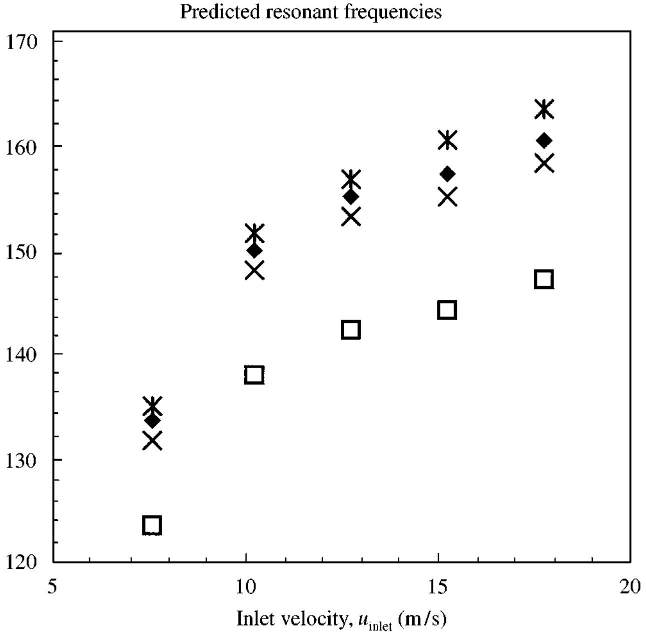


Figure 5. Predicted and measured resonant frequencies. * Experiment; ◆ no feedback-acoustic modes: ☐ heat release ∝ mass flowrate; × Bloxsidge feedback model.

a simple acoustic model with a pressure antinode at the dump plane. The relative phase of $-90°$ between the velocity and the heat release fluctuations at the dump plane is predicted by the Bloxsidge model whereas the feedback model assumes perfect coupling between the flowfield and heat release so that the pressure and heat release will be in phase at the dump plane. The acoustic model provides no information on the heat release/pressure-phase relationship. For the higher inlet velocities, the predictions from the Bloxsidge (and the acoustic) model deviate more significantly from the experimental resonant frequency. It is likely that this is due to the assumption of an infinitely thin-flame sheet with the heat input concentrated at a single plane being less valid at the higher inlet velocities. It is likely that a model incorporating a heat release zone such as the primary zone evident from the velocity/pressure measurements would provide a more accurate representation of the system. It should be noted that in addition to the prediction of the resonant frequency, an adequate model for combustion instability will be required to predict the onset of instability. This aspect has not been addressed in this paper.

5. CONCLUSIONS

For the dump combustor geometry investigated in this study, strong acoustic oscillations were observed over the entire flammability range. From the results obtained, the following conclusions can be drawn.

- The phase between temperature and wall pressure at the quarter-wave resonance was directly proportional to Strouhal number.

- The phase between fluctuating velocity and wall pressure exhibited two zones, the first, close to the dump plane, where the phase increases linearly with Strouhal number indicating convection of burning vortices and the second, further downstream, where the phase was constant with the acoustics controlling the system.
- Predictions from the Bloxsidge model to describe the coupling between the flowfield and the heat release agreed well with measured frequencies. The incorporation of a heat release zone in modelling should provide a more realistic model.

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