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The non-linear thermo-acoustic response of a small swirl burner

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ABSTRACT

The non-linear response of a swirl stabilised, lean premixed flame (CH_4/air) was determined by forcing the flame acoustically at frequencies between 40 and 200 Hz with increasing amplitude. Measuring the chemiluminescent emission from OH^* with a photodiode sensor and calculating the flame transfer function, a linear response to increasing amplitude was observed at 40 and 60 Hz for all amplitudes with an equivalence ratio $\phi = 0.56$. However, between 80 and 200 Hz the flame response exhibited non-linear characteristics for r.m.s velocity fluctuations greater than 20% of the mean flow velocity. With $\phi = 0.48$, even 60 Hz became non-linear. Phase-locked Particle Image Velocimetry and Intensified CCD imaging were deployed at three amplitudes for detailed study of the flame and flow field response to forcing. At low frequencies the flow field was characterised by a pulsating inner recirculation zone, whilst at all frequencies the outer recirculation zone was modified by vortices rolling up the annular jet. As the forcing amplitude was increased, the effect on the flame shape became more pronounced, with large variations in flame volume at low frequencies and flame extinction due to stretching of the flame around the roll-up vortices at the higher frequencies. The results indicate different driving mechanisms behind the flame response at low and high frequencies. At low frequencies the flame response is governed by equivalence ratio fluctuations due to the 'stiff' fuel system and the volumetric fluctuations of the input air. At the higher frequencies the response is governed by flow field features such as vortex roll-up.

1. Introduction

With the commissioning of a large number of industrial gas turbines over the last 20 years, there has been a considerable concentration of combustion research effort on the thermo-acoustic response of gas turbine burners. This is because the drive for lower NO_x emissions has led to operation in the very lean premixed mode where the flame is often less stable. Naturally occurring fluctuations in the velocity of the incident premixture can then be amplified by the flame. If the response is strong enough at particular frequencies in the spectrum, acoustic damping is overcome and self-excited oscillations result. These settle to a 'limit cycle' of amplitude determined by the damping and the limited forcing as the amplitude increases [1]. The resulting 'hum' may nevertheless be sufficient to inflict fatigue damage on the turbine blades.

Subtle changes to the configuration of the burner can offer the least painful route to the suppression of these instabilities, either by moving the frequencies of peak response away from the resonances of the turbine system, or by suppressing the response at a given frequency. A number of the mechanisms of response have been reviewed by Lawn and Polifke [2]. While linear models based on the convective time-delay of disturbances in the burner and the flame are often sufficient to predict which frequencies will be unstable [3,2], there have been few attempts to predict the amplitude of limit cycles. This requires a model for the departures of the flame response from linearity as the amplitude increases [1]. Huang and Yang [4] review the general theory of non-linear response in the thermoacoustic context. In some cases, the non-normality of the eigenmodes resulting from the thermoacoustic interactions must also be taken into account in predicting the response [5].

Approaches based on the kinematics of the flame front seek to extend the success in predicting non-linear behaviour in laminar conical and V-shaped flames, for example by Schuller et al. [6]. Retaining the constant flame speed assumption for turbulent flows, Lieuwen [1] showed that non-linear behaviour is evident once the flame wrinkling becomes so intense that cusps are formed. However, both Bellows et al. [7,8] and Balanchandran et al. [9] have observed, using Planar Laser Induced Fluorescence in swirling and non-swirling premixed combustion respectively, that practically the non-linearity is likely to be associated with Kelvin–Helmholtz ring vortices shed from the burner outlet. These vortices are convected along the shear layers and distort the heat release process, sometimes to the point of extinction of the flame front. In Balanchandran et al. [9], it was observed that the greatest non-linear effects occurred in a mid-frequency range in which there was flame annihilation by the vortices. In Bellows et al.'s work [7,8], there

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was an additional mechanism of non-linearity in the periodic lifting of the entire flame, while in Thimuluru and Lieuwen [10], the observed non-linear behaviour was attributed to four different mechanisms involving the dynamics of the shear layer, and internal and external recirculation zone fluctuations.

From first principles using an unsteady Reynolds-averaged Navier–Stokes approach, Armitage et al. [11] have successfully predicted the transition to non-linear behaviour in Balanchandran's data. However, a limit cycle was not predicted. Dowling [12] used an empirical function to describe the response of a confined bluff-body stabilised flame and showed that the frequency of self-excitation was little changed as the limit cycle was reached. Extending the analysis of a number of investigators, in the form summarised by Fleifil et al. [13], the movement of the flame front was described [14]. With certain assumptions specific to the burner geometry and constant flame speed, the equations were solved numerically and previous experimental observations reproduced qualitatively. Noiray et al. [15] also achieved quantitative agreement for limit cycling with the 'flame describing functions' they measured for a multi-flame burner anchored on a perforated plate. Peracchio and Proscia [16] had a similar approach in calculating the response of a model gas turbine combustor to the non-linearity associated with flame extinction at low equivalence ratios in the case where the equivalence ratio fluctuates. The parameters in their model had to be determined empirically to represent (albeit approximately) the limit cycle behaviour as the mean equivalence ratio was varied; the implied flame shape variation was not worked out.

The present experimental contribution explores the response of a small swirl-stabilised premixed burner to forced excitation at various amplitudes, with a view to determining the mechanisms for departure from a linear response. In common with most practical burners of this design, the fuel injection was not choked, although it was through a very high impedance supply line up to the fuel plenum chamber. Data for the self-excited OH chemiluminescent emission from this same burner, acquired with photodiodes, have been previously reported [17,18], and the linear response has subsequently been modelled with some success [2,19,20]. For the new investigation, photodiode data from the flame with forced excitation [21] have been supplemented by phase-locked Particle Image Velocimetry (PIV) and Intensified Coupled Charge Discharge (ICCD) chemiluminescence imaging, providing far greater detail of the local conditions at each stage of the cycle [22,23]. Data have now been acquired over the frequency range 40–200 Hz, with three levels of excitation. From the flame images and velocity fields, some features of non-linearity have been identified.

This paper continues with an account of the apparatus and of how the data were acquired. This is followed by a short section describing the character of the response of the flame to excitation, as registered by a photodiode. The data acquired by the PIV and ICCD chemiluminescence techniques are then described briefly, before the implications of all the results taken together are brought out in Section 5. Some comparisons with the results of previous investigations are also undertaken there.

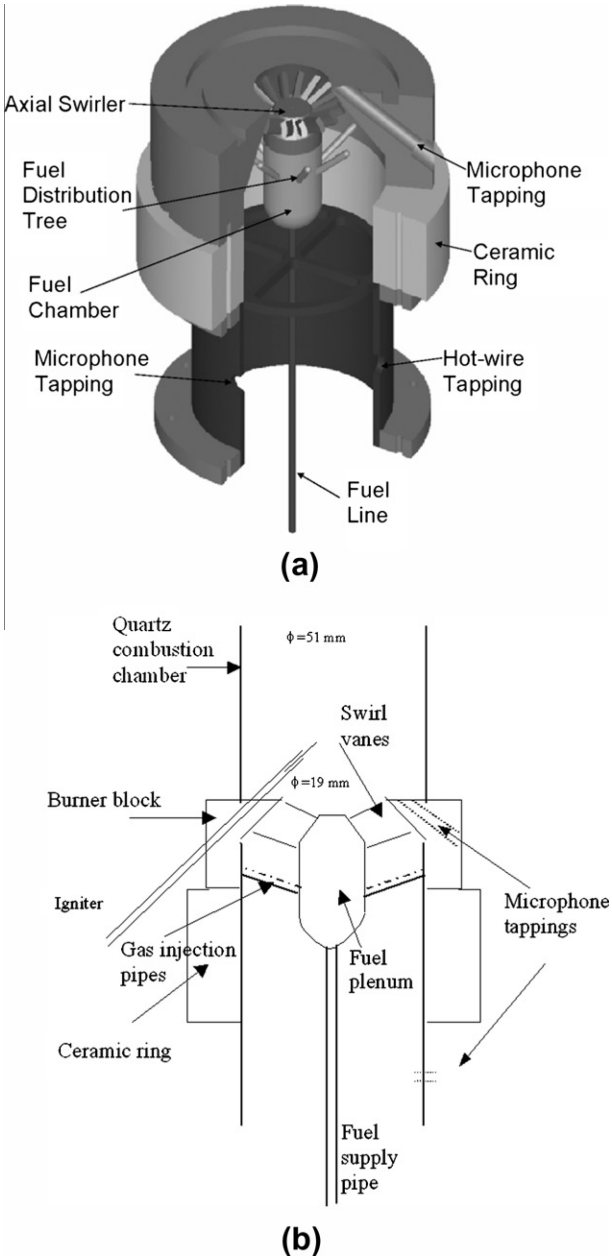

Fig. 1. The burner configuration.

2. Experimental arrangement and measurement technique

2.1. Burner configuration

The burner geometry is shown in Fig.1. The flame was stabilised by a 16-bladed axial swirler with blade angles adjusted to produce a swirl number of approximately 0.5. The swirler was positioned in a conical converging section so that all fuel and air passed through the swirler vanes before entering the combustion chamber through the 19 mm diameter burner exit. The fuel, commercial grade methane, was delivered just upstream of the vanes. Qualitatively, the fuel gas supply system had the characteristics of some full-scale commercial burners, in that gas injection was through a 'tree' of eight pipes spreading radially across the air-flow with holes distributed along the downstream edges of the branches to achieve a high degree of mixing in their wakes (Fig. 1). To investigate whether there were significant equivalence ratio fluctuations, comparison was made with a separate experiment in which the mixing took place in an upstream chamber.

For the purpose of PIV image acquisition the air was seeded, after measurement of volumetric flow rate, from two solid-particle units (type 3400a fluidised bed generators), each using aluminium oxide particles of size 3 μm. The seeding caused the flame to appear orange in colour, instead of light blue. When no excitation was imposed the visual flame took the shape of an inverted cone with a half angle of 34°. The flame had a quasi-steady blow-off limit at an equivalence ratio of 0.33. All of the current experiments were conducted with an equivalence ratio of either 0.56 or 0.48.