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Azimuthally forced flames in an annular combustor

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Abstract

The application of azimuthal acoustic forcing to flames in a laboratory scale annular combustor is demonstrated in the present paper, which not only allows large amplitude azimuthal modes to be excited, but permits control to be exerted over their frequency, amplitude, and their modal dynamics, including parameters such as the spin ratio and orientation. The effect of forcing frequency is investigated, and it is found that the excitation can be well controlled into a standing wave oscillation over a range of amplitudes for selected frequencies. However, close to the natural frequency of the system, the modal dynamics cannot be well controlled, and instead these tend towards their self-excited state, resulting in a mixed mode. Comparing the phase-averaged structure of the forced and self-excited responses for similar operating conditions, illustrate similar flame dynamics, making this novel forcing approach extremely useful for the study of these instabilities in annular systems.

Keywords: Gas turbines; Azimuthal modes; Combustion instabilities; Acoustic forcing

1. Introduction

It is well known that azimuthal thermoacoustic instabilities can arise in annular combustion chambers under certain operating conditions, considerably reducing their operable range and threatening their structural integrity. Recent work [25,5,11,20] has demonstrated that the behaviour of these azimuthal instabilities is both richer and more complex than longitudinal modes in isolated single flame systems, which omit some dynamical features observed in annular systems. A crucial distinction of azimuthal instabilities in annular systems is that they are subject to transverse pressure disturbances. Pressure fluctuations can propagate around the annulus in either a clockwise (CW) or anti-clockwise (ACW) sense, and as the amplitude of these waves varies with time, the mode of oscillation can switch rapidly between spinning and standing modes [22,24,16,11], affecting the flame dynamics and heat release response [6,7].

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While this modal response is important for both prediction and control of instabilities, the mechanisms that drive this are not well understood, however, they can be investigated directly through high fidelity numerical simulations [22] and experiments [24,5,16,6]. An important issue is the effect of transverse velocity fluctuations and the interaction of multiple flames on the Flame Describing Function (FDF), which relates the response of the unsteady heat release rate to a characteristic fluctuating velocity scale and is a crucial input for Helmholtz solvers [14] and reduced order models [8,21,15]. For example the classical FDF formalism is not expected to hold in cases which include multiple interacting flames, and if transverse velocity fluctuations can alter the heat release in non-symmetric flames [1] then a complete FDF description of this may be required to couple both the transverse and longitudinal velocity oscillations to the heat release rate. To investigate the flame response and derive FDFs, longitudinal forcing has been applied to isolated single flames [2,18] and multiple flames [23,9]. Longitudinal forcing of multiple flames in an annular combustor has also been investigated [9], however, it is unclear how well this approach replicates the true transverse nature of self-excited azimuthal instabilities.

Several investigators have used loudspeakers positioned at either end of channels or pipes, which are long in the transverse sense relative to the flow direction [17,13,19] in order to study transversely forced flames which better approximate realistic conditions. Through this approach it is possible to create and control both standing and travelling acoustic modes which propagate normal to the flame, permitting investigations into the flame response at different locations within the mode shape. However, the azimuthally symmetric nature of an annular chamber prohibits the direct application of such an approach in annular geometry as no end locations exist around the annulus, and inserting a wall into the chamber at one radial location would break the rotational symmetry which is known to have a number of important effects on the modal dynamics [24,7,4,3].

In the present paper a novel application of the azimuthal forcing method described by Gelbert et al. [10] is presented, in which acoustic forcing is applied directly to the annular combustion chamber in order to control for the first time not only the amplitude and frequency of pressure oscillations, but also the resultant acoustic mode shape and orientation; realising a significant step towards understanding both the flame dynamics and the response of flames in annular combustion chambers. The approach is also shown to be non-invasive, in that the mean and phase averaged flame structure shows no significant effect of forcing, and instead is very similar to the self-excited response.

2. Experimental methods

2.1. Annular combustor and acoustic forcing

Figure 1 shows the experimental setup of the annular combustor which is described in detail in refs. [25,24]. 18 premixed C_2H_4-air flames were arranged around a circle of diameter of $D_a = 170$ mm, supplied from a common plenum ($L_p = 200$ mm, $D_p = 212$ mm). Inside the plenum is a honeycomb flow straightener, a layer of wire wool, a series of grids, and a hemispherical body of diameter $D_h = 140$ mm for flow conditioning and acoustic damping. Each burner consists of a circular tube ($L_t = 150$ mm, $D_t = 18.9$ mm), a centrally located conical bluff-body ($d_{bb} = 13$ mm) fitted with a six-vane swirler with a vane angle of 60° which is positioned 10mm upstream. A detailed schematic of the swirler was provided in [24]. In the present investigation, the swirlers turn the flow anticlockwise (ACW) when viewed from above (downstream). This 18 flame configuration results in non-dimensional separation distance of $S/D_t = 1.56$.

The annular combustion chamber consists of inner and outer steel tubes of $D_i = 127$ mm and $D_o = 212$ mm with lengths of $L_i = 130$ and $L_o = 300$ mm respectively. Acoustic forcing was generated using two loudspeakers (Adastra 60 W compression drivers) mounted on water cooled stand-off pipes, which had an inner diameter of $D_F = 20$ mm and a length of $L_F = 120$ mm, and were located on diametrically opposite sides of the outer steel tube, at a height of $H_F = 40$ mm. An Aim and Thurlby Thandar TGA1242 40 MHz arbitrary waveform generator was used to generate a sinusoidal signal which was separated into two before being amplified and sent to the loudspeakers. The polarity of one signal was reversed in order to create a phase difference of 180° between the speaker pressure oscillations in order to excite a standing wave at the first azimuthal mode of chamber. The response to both frequency and amplitude changes were investigated.

2.2. Operating conditions and mode characterisation

Four Alicat mass flow controllers with ranges of 0–2000 lpm for air and 0–100 lpm for C_2H_4 were used to regulate reactant flow rates, with a measurement accuracy of 0.8% of the reading plus ±0.2% of the full scale. A bulk velocity of $\langle\overline{U}\rangle = 18$ m/s results in a Reynolds number of $Re = 15,000$ based on the bluff-body diameter. The equivalence ratio was fixed at $\phi = 0.8$ for the forcing experiments; an operating condition at which high amplitude self-excited instabilities are not observed [25]. Furthermore, as the system does not exhibit thermoacoustic triggering, the