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Feature Article

Flame dynamics and unsteady heat release rate of self-excited azimuthal modes in an annular combustor

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ABSTRACT

This paper presents an experimental study into the structure and dynamics of the phase-averaged heat release rate during self-excited spinning and standing azimuthal modes in an annular combustion chamber. The flame response was characterised using two methods: high-speed OH^* chemiluminescence imaged above the annulus to investigate the structure of the phase-averaged fluctuations in heat release rate, and high-speed OH-PLIF measured across the centreline of two adjacent flames to investigate phase-averaged flame dynamics. Two-microphone measurements were obtained at three circumferential locations to determine the modes and the amplitude of the velocity fluctuations. It was found that the flame responds differently to spinning and standing wave modes. During standing wave modes, the amplitude of the unsteady heat release rate of each flame (sector) varied according to its location in the mode shape with maximum fluctuations occurring at the pressure anti-nodes and minimum fluctuations occurring at the pressure nodes. At the pressure anti-nodes, peak fluctuations result from the production of flame surface area by axisymmetric flame motions caused by the modulation of flow at the burner inlet by the pressure fluctuations. However, at the pressure nodes, an anti-symmetric, transverse flapping motion of the flame occurred producing negligible unsteady heat release rate over the oscillations cycle via the mechanism of cancellation. During spinning modes, the structure of the heat release rate was found to be asymmetric and characterised by the preferential suppression of shear layer disturbances depending on the spin direction.

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1. Introduction

Most combustion systems in modern gas turbines for power and propulsion use annular combustion chambers. Self-excited thermo-acoustic instabilities are a well known and recurring problem in the development of new combustion systems. In annular combustion chambers these instabilities tend to excite azimuthal modes as the circumference typically forms the longest dimension [1]. These instabilities occur when acoustic waves propagating azimuthally around the combustion chamber constructively interact with fluctuations in the heat release rate generating pressure fluctuations which grow in amplitude until a limit-cycle is reached.

Recent numerical computations of an annular combustor by Wolf et al. [2] showed that over the simulation time, the self-excited azimuthal modes switched back and forth between spinning and standing wave modes. Similar observations have been reported in experiments by Worth and Dawson [3] and Bourgouin et al. [4] in simple laboratory-scale annular combustion chambers. In geometrically symmetric annular geometries, acoustic waves that travel in the clockwise (CW) and anti-clockwise (ACW) azimuthal directions are not coupled with each other. This is because there is no wall or sudden change in impedance to break the symmetry and couple the azimuthal waves. Consequently, self-excited azimuthal modes exhibit time-varying amplitude and phase and are therefore rarely pure rotating or standing wave modes but a mix or composite of the two. Constructing probability density functions (*p.d.f.s*) of the amplitudes A_+ and A_- of the azimuthal waves, Worth and Dawson [3] showed that a statistical prevalence for spinning or standing modes depended on the flame separation distance when all burners were equipped with swirlers having the same sign. When alternating burners were fitted with swirlers of opposite sign to eliminate bulk swirl, a statistical preference for standing wave modes was observed in all cases. Bourgouin et al. [4] proposed a spin ratio *SR* (see Section 2.3) to characterise azimuthal modes, a simple but elegant normalisation of the difference between the magnitude of the amplitudes of the clockwise and anti-clockwise acoustic waves divided by their conjugate, such

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that $SR = 0$ corresponds to a perfect standing mode and $SR = \pm 1$ correspond to perfect spinning modes in either direction. A *p.d.f.* of SR from their experiments showed a statistical preference for a weak CW spinning mode.

Prior to these recent studies, our understanding of azimuthal modes has predominantly relied on linear stability analyses within simplified acoustic network descriptions of the combustion system [5–9]. The non-linear flame response is then modelled, usually using a flame transfer/describing function (FTF/FDF) based on an equivalent single, typically axisymmetric flame. This relates normalised global fluctuations in heat release rate $q'/\overline{Q}$ produced at each burner to the normalised axial velocity fluctuations $u'/\overline{U}$ at the burner inlet over a range of frequencies and amplitudes, usually with the addition of a time-delay. The important concept is that the flame response is assumed to be invariant and therefore always have the same FTF/FDF. A corollary of this is that interactions with neighbouring flames does not occur. The LES of an annular helicopter engine by Staffelbach et al. [10] is one case where these assumptions have been demonstrated sufficient. In that study, the self-excited azimuthal mode was mixed but can be considered closer to a spinning mode than a standing mode as ratio of amplitudes of the CW and ACW waves was $A_-/A_+ = 0.33$. During spinning modes, where $SR \rightarrow \pm 1$, velocity fluctuations through each burner are driven by the pressure nodes travelling around the annulus at the speed of sound, $\bar{c}$. Generality would require these assumptions to be demonstrated sufficient for standing wave and all composite modes where SR takes on intermediate values.

Despite numerical and experimental evidence to the contrary [2–4,11], most models ultimately predict that only spinning modes give rise to stable limit cycle oscillations in symmetric annular combustion chambers, i.e. identical burners that are evenly spaced around the annulus and assumed to have the same FTF [8,12,13]. As a means of controlling instabilities, Noiray et al. [13] investigated the effect of asymmetric heat release rate around the annulus by introducing a non-uniform distribution of FTFs. Depending on the degree of asymmetry, their model predicted that standing wave or composite modes were stable. More recently, Noiray and Schuermans [14] added stochastic forcing in the form of broadband noise into their model with symmetric heat release rate around the annulus, in an effort to reconcile differences between their predictions and the simulations of Wolf et al. [2]. They found that noise can cause the modes to jump back and forth between the two spinning modes but stable standing wave modes, as reported in the symmetric annular configurations [2–4], were not found. Currently, most thermo-acoustic models cannot explain why standing modes in symmetric annular chambers should be stable, despite being observed in both experiments and numerical simulations. However, a recent study by Ghirardo and Juniper [15] extended the model of Noiray et al. [13] to include interactions between the azimuthal acoustic velocity and the unsteady heat release rate and found that standing, spinning and mixed modes can be stable.

One of main challenges is to develop physics based descriptions of the unsteady heat release rate during spinning, standing and composite self-excited azimuthal modes. This requires experimental or numerical data which has only recently started to become available. Worth and Dawson [3] observed that the unsteady heat release rate around the annulus was different for spinning and standing wave modes. During spinning wave modes, the amplitude of $q'/\overline{Q}$ produced by each burner around the annulus was approximately constant consistent with the findings of Staffelbach et al. [10]. However, during standing wave modes the amplitude of heat release rate fluctuations varied spatially around the annulus with peak fluctuations produced at the pressure anti-nodes and negligible fluctuations produced at the pressure nodes. Within a one-dimensional framework, in the absence of velocity fluctuations at the pressure nodes, i.e. $u'/\overline{U} \rightarrow 0$, flames should be steady with a constant heat release rate $q'/\overline{Q} \rightarrow 0$. However, recent studies of transversely forced flames have shown that complex flame dynamics actually occur at pressure nodes and yet produce negligible $q'/\overline{Q}$. Connor and Lieuwen [16] investigated the flow field response of an annular jet at a pressure anti-node and node under cold flow and reacting conditions using two-dimensional particle image velocimetry (PIV). At the pressure anti-node, transverse velocity fluctuations, v', were small, and an axisymmetric response was observed which is consistent with the flame dynamics from longitudinal forcing, see Refs. [17,18] for two examples. At the pressure node, v' components of $\approx 30-40\%$ of the bulk velocity was reported causing adjacent sides of the annular jet to oscillate in anti-phase which they suggested was due to the amplification of helical modes. A recent paper by Lespinasse et al. [19] considered the effect of transverse forcing of a conical laminar flame when placed at different locations between the pressure node and anti-node. They also observed that v' is amplified at the acoustic velocity anti-node inducing transverse flame motions. Using a different acoustic forcing arrangement, transverse forcing in the plenum upstream of a flame positioned at a pressure node (acoustic velocity anti-node), Hauser et al. [20] also observed a strong asymmetric flame response. Together these studies indicate that v' plays a mechanistic role in ensuring that $q'/\overline{Q} \rightarrow 0$ at pressure nodes.

Previous studies focused on the effect of flame spacing on the global heat release response of ACW spinning modes [11] and the time-varying amplitude and phase behaviour of self-excited azimuthal modes [3], however this paper investigates the unsteady flame dynamics during spinning and standing wave modes in an effort to improve our understanding of the physical mechanisms that drive the unsteady heat release rate for azimuthal modes. To do this, the flame response is characterised using two methods; high-speed chemiluminescence imaging and high-speed OH-PLIF. Combined, these measurements provide new physical understanding of the structure of the heat release rate and the local flame dynamics. In the next section the apparatus, operating conditions, and measurement techniques are presented. In Section 3 the effect of flame spacing on the mean flame structure is described. In Section 4, the phase-averaged structure of the global heat release rate during spinning and standing wave modes viewed from above the annulus is presented and discussed. The phase-averaged planar flame dynamics are then presented in Section 5.

2. Experimental methods

2.1. The model annular combustor

The annular combustor has been described previously in Refs. [3,11]. As shown in Fig. 1, it consists of 12, 15, or 18 equidistantly spaced bluff-body stabilised turbulent premixed flames arranged around a circle of diameter $D_a = 170$ mm. Each flame is supplied from a cylindrical plenum chamber of length $L_p = 200$ mm having an inner diameter of $D_p = 212$ mm. Inside the plenum a honeycomb flow straightener, a layer of wire wool, a series of grids, and a hemispherical body of diameter $D_h = 140$ mm are used for flow conditioning and acoustic damping. Premixed C_2H_4/air flows from the plenum into 150 mm long circular tubes having an inner diameter $D = 18.9$ mm fitted with a centrally located conical bluff-body of diameter $d_{bb} = 13$ mm. The bluff bodies are mounted flush with the combustion chamber resulting in a blockage ratio of 50%. The inlet tubes were fixed between upper and lower plates, which could be changed to 12, 15 or 18 flame configurations corresponding to non-dimensional flame separation distances of $S = 2.33D$, $S = 1.87D$ and $S = 1.56D$, where S is defined as the arc distance between the bluff-body centres described in Fig. 1(b). Each bluff body was fitted with a six-vane swirler with a vane angle of 60°

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