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The effect of baffles on self-excited azimuthal modes in an annular combustor

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Abstract

In this paper the effect of inserting baffles on the self-excited azimuthal modes and unsteady heat release rate in an annular combustor are investigated experimentally. Particular attention is given to their effect on the time-varying behaviour of azimuthal modes observed in recent experiments and Large Eddy Simulations (LES) in azimuthally symmetric annular chambers. This time-varying behaviour causes the azimuthal modes to switch back and forth between spinning and standing wave modes. With the addition of a single baffle, the azimuthal symmetry of the chamber was broken leading to a coupling between the clockwise (CW) and anticlockwise (ACW) azimuthal acoustic waves. This eliminated the time-varying behaviour and promoted standing wave modes. It was found that three or more baffles were required to achieve significant damping of the modes. Since almost perfect standing wave modes occurred with the addition of a single baffle, high-speed chemiluminescence measurements were obtained to characterise the unsteady heat release rate at the pressure node and anti-node. Previous studies have shown that maximum and minimum heat release rate is produced at the anti-nodes and nodes respectively. As found previously, peak fluctuations at the anti-nodes result from axisymmetric fluctuations in heat release rate caused by pressure fluctuations driving axial mass flow fluctuations at the burner inlet. However, at the pressure nodes, an anti-symmetric structure was observed producing negligible heat release rate via the mechanism of cancellation. This latter result suggests that transverse velocity fluctuations play an important mechanistic role in ensuring that negligible heat release rate is produced at the node.

Keywords: Gas turbines; Azimuthal modes; Combustion instabilities; Baffles; Damping

1. Introduction

The occurrence of self-excited azimuthal modes are a well known problem in the design and development of annular combustion chambers for gas turbines [1]. At present, the underlying physical mechanisms that excite and drive azimuthal modes are poorly understood and are often only discovered during full annular tests. However, recent LES of full annular combustors with realistic geometries [2,3] and experiments in simplified annular combustion chambers [4,5,6] have begun to elucidate some of the key physical mechanisms. In rotationally symmetric annular

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geometries, i.e. a uniform geometry equipped with identical equally spaced burners, acoustic waves propagate azimuthally in the clockwise (CW) and anti-clockwise (ACW) directions but are not coupled with each other. Both LES and experiments have shown that self-excited azimuthal modes in symmetric chambers exhibit time-varying amplitude and phase causing the modes to switch back and forth between spinning and standing wave modes in time [3,5,6,7].

In terms of passive damping and control, Helmholtz resonators and circumferential staging are strategies frequently used in gas turbines. Both approaches involve breaking azimuthal symmetry to control or damp azimuthal modes. Stow and Dowling [8] developed a network model to calculate the stability of azimuthal modes in an annular geometry and identify the optimum configuration of Helmholtz resonators for damping. The addition of a single Helmholtz resonator broke the azimuthal symmetry of the combustor resulting in the coupling of the CW and ACW azimuthal waves which promoted standing wave modes. For damping, a minimum of two resonators were needed and optimal locations were discussed. Noiray et al. [9] used non-uniform distributions of Flame Transfer Functions (FTF) to model the effect of circumferential staging. By altering the degree of asymmetry it was found that either standing wave or composite modes were stable. A low-order model to assess the effectiveness of circumferential staging was recently developed by Parmentier et al. [10]. The stability of azimuthal modes in symmetric (same burners) and asymmetric (a combination of different burners) annular geometries was carried with the latter providing better passive damping.

In this paper we investigate how inserting baffles into an annular combustor can control and/or damp azimuthal modes. Baffles have been widely used for passive damping of transverse instabilities in rocket engines [11,12]. In rocket engines it has been observed that the damping effects of baffles result from a range of mechanisms which include, the production of vorticity due to transverse velocity passing over the baffle, modification to the chamber acoustics by creating baffled compartments that limit the effect of the transverse acoustic velocity, and increasing the number of baffles which reduces the frequency by increasing the path length. In this paper, several different baffle configurations are investigated with particular emphasis placed on how baffles affect the time-varying behaviour of azimuthal modes.

2. Experimental methods

2.1. Annular combustor

Figure 1 shows the experimental setup of the annular combustor which is described in detail in Refs. [4,5]. Twelve premixed C_2H_4-air flames were arranged around a circle of diameter of $D_a = 170$ mm and were fed from a common plenum ($L_p = 200$ mm, $D_p = 212$ mm). Inside the plenum was 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. As a result, the pressure fluctuations in the plenum were negligible. 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° positioned 10 mm upstream. A detailed schematic of the swirler was provided in [5] and turns the flow anti-clockwise (ACW) when viewed from above the annulus.

The annular combustion chamber consists of inner and outer steel tubes of $D_i = 127$ mm and $D_o = 212$ mm with lengths of $L_i = 130$ mm and $L_o = 300$ mm respectively. Since the combustor is exposed to the atmosphere the modes are not purely azimuthal and have a longitudinal component along L_o. However, L_o is much greater than the flame length (≈30 mm) and the corresponding longitudinal pressure variation was negligible over greater than five flame lengths which was verified using an acoustic solver. We therefore neglect any longitudinal dependence of the mode in our analysis and treat the modes as azimuthal only.

The effect of inserting one or more simple flat stainless steel radial baffles on the self-excited azimuthal modes was investigated. In the absence of baffles the annular combustor is azimuthally symmetric. Baffles with a width, $w_b = 41.6$ mm, height of $h_b = 65$ mm and of thickness 1.5 mm were mounted perpendicularly on the inner annular wall in between burners to minimise changes to the flame structure. These dimensions were chosen as w_b spanned the annular gap to form a wall whereas h_b was twice the flame height to ensure complete separation of the flame and immediate post-flame regions. The effect of five different baffle combinations, denoted by N_b as shown in Fig. 1(c) were tested. For $N_b = 2$ both symmetric and asymmetric configurations were tested, denoted $N_b = 2S$ and $N_b = 2A$ respectively.

2.2. Operating conditions and mode characterisation

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 constant time-average bulk velocity of $\overline{U} = 18$ m/s at the bluff body exit was maintained during all experiments corresponding to a Reynolds number of $Re = 15{,}000$ based on the bluff-body diameter. Hot wire measurements taken at 4 quadrant locations verified the bulk flow was uniform to within 1%. The