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Effect of equivalence ratio on the modal dynamics of azimuthal combustion instabilities

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Abstract

The present paper investigates the effect of equivalence ratio on the modal dynamics of self-excited azimuthal combustion instabilities in a laboratory-scale annular combustor. It is shown that operating at different equivalence ratios not only affects the mode of oscillation (whether the instabilities are mixed, or predominantly spinning or standing modes), but also the way in which mode switching between these states occurs. Using pressure time-series data obtained at multiple locations around the annulus the phenomenon of mode switching is investigated through the spin ratio, the orientation of the nodal lines and the envelope of the pressure oscillations. These three parameters all suggest that mode switching events occur almost periodically, and over azimuthal convective time scales. Moreover, analysis of the spin ratio and orientation of the nodal lines show that these parameters are correlated, and that their mean rates of change or trajectories also have a preferred direction. Therefore, these quantities were found to oscillate backwards and forwards in-phase with each other, as opposed to the mode simply rotating in one direction, providing new insight into the nature of modal dynamics of self-excited azimuthal modes.

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Keywords: Gas turbines; Azimuthal modes; Combustion instabilities; Modal dynamics; Mode switching

1. Introduction

Recent studies on the nature of azimuthal modes in annular combustors have shown that due to their discrete rotational symmetry, instabilities in these systems can give rise to more complex behaviour [21,13,23,5,9,19] compared with longitudinal modes in isolated single flame systems (for example [2]), which omit some dynamical features observed in annular systems. One of the important differences between these systems is that flames in annular combustion chambers are subjected to azimuthal (or transverse) pressure waves, and due to their symmetry, pressure fluctuations travel around the annulus in either clockwise (CW) or anti-clockwise (ACW) directions. Furthermore, evidence so far suggests that in the case of turbulent swirling flames pure spinning or standing modes are rare, and that oscillations are characterised

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Nomenclature

ω	angular frequency
ϕ	equivalence ratio
Σ	swirl number
θ_k	pressure measurement location
θ_{nl}	nodal line location
A_+	amplitude of ACW pressure wave
A_-	amplitude of CW pressure wave
C	combined pressure indicator
D_a	mean annular diameter
D_h	hemispherical body diameter
D_p	plenum diameter
D_t	inlet tube diameter
d_{bb}	bluffbody diameter
D_i	annulus inner diameter
D_o	annulus outer diameter
L_p	plenum length
L_t	inlet tube length
L_i	annulus inner length
L_o	annulus outer length
p_k	pressure fluctuations
R	annulus radius
S	separation distance
SR	spin ratio
U	inlet velocity
U_t	tangential velocity
v_θ	mean azimuthal velocity component

by time-varying amplitude and phase of the acoustic waves (A_+ and A_-) travelling in opposite directions around the annulus [11,21,22,14]. Rapid changes in the magnitude of these component waves generates mixed azimuthal modes that can exhibit a time varying statistical preference for predominantly spinning and standing modes. This rapid mode switching behaviour is what is meant by the term modal dynamics [18,11].

A number of theoretical studies have suggested that either the oscillation amplitude or the degree of asymmetry in the heat release or the flow may control the modal dynamics [17,18,11,3,4]. Moreover, given that these instabilities occur in practical flows which are characterised by their highly turbulent nature, it has also been proposed that turbulence plays an important role in mode switching between spinning and standing states [18,11]. Pressure time-series have been used to observe mode switching in recent experimental and numerical studies [21,22], which can be analysed in terms of the ratio of A_+/A_-, a spin ratio [5], or through the phase change of the combined pressure indicator $C(t)$ (introduced later in Section 2.2). These studies have shown that mode switching proceeds slowly in comparison with the acoustic timescales. A connection has also made between the azimuthal symmetry of the magnitude of the heat release fluctuations and the mode of oscillation, and the mean azimuthal velocity profile [22]. However, because the mode switching phenomenon has only recently been reported it has yet to be properly investigated or explained.

This is important as low-order approaches typically apply a flame response model to couple the unsteady velocity and heat release at each flame, and therefore model the flame response [8,20,12]. However, given that the time varying structure of the flames and therefore their response is dependent on the modal dynamics and mode orientation [6,7,16,15,10], then a complete flame describing function (FDF) may be required to couple both the transverse and longitudinal velocity oscillations to the heat release rate, in order to take account of transverse velocity fluctuations, which can alter the heat release in non-symmetric flames [1].

This paper is a first step in this direction by characterising the prevalence, time-scales, and connection between different mode parameters which occur during mode switching events. An experimental approach is particularly useful for such an investigation, as relatively long run times ensure many thousands of oscillation cycles are captured, making these suitable for investigating events occurring over long time-scales. We present results describing how the modal dynamics vary with equivalence ratio and show how mode-switching is slow in comparison with the acoustic time-scales and occurs over time-scales which are of the same order as bulk convection times. Following this, the spin ratio and orientation of the nodal lines are related statistically, demonstrating that they are dynamically connected and providing new insight into the physical mechanisms responsible for mode switching.

2. Experimental methods

2.1. Laboratory scale annular combustor

Figure 1 shows the experimental setup of the annular combustor which is described in detail in Refs. [23,22]. 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. 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. 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 10 mm upstream. A detailed schematic of the swirler was provided in [22]. In the present investigation, the swirlers turn the flow anti-clockwise (ACW) when viewed from above (downstream). This 18 flame

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