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Thermo-acoustic instabilities in lean premixed swirl-stabilized combustion and their link to acoustically coupled and decoupled flame macrostructures

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Abstract

We investigate the onset of thermo-acoustic instabilities and their link to the mean flame configurations – or macrostructures – under acoustically coupled and decoupled conditions. Methane–hydrogen mixtures are used to explore the role of the fuel in changing the flame macrostructure, as determined by chemiluminescence, as the equivalence ratio (ϕ) varies. We observe four different configurations: a columnar flame (I); a bubble-columnar flame (II); a single conical flame (III); and a double conical flame (IV). We also observe different thermo-acoustic modes in the lean regime investigated, $\phi \in [0.5 - 0.75]$, that correspond to different flame configurations. By changing the combustor length without affecting the underlying flow, the resonant modes of the combustor are shifted to higher frequencies allowing for the decoupling of heat release fluctuations and the acoustic field over a range of equivalence ratio. We find that the same flame macrostructures observed in the long, acoustically coupled combustor arise in the short, acoustically decoupled combustor and transition at similar equivalence ratios in both combustors. The onset of the first fully unstable mode in the long combustor occurs at similar equivalence ratio as the flame transition from configuration III to IV. In the acoustically decoupled case, this transition occurs gradually starting with the intermittent appearance of a flame in the outer recirculation zone (ORZ). Spectral analysis of this phenomenon, referred to as "ORZ flame flickering" shows the existence of an unsteady event occurring over a narrow frequency band centered around 28 Hz along with a weaker broadband region at lower frequency in the range [1–10] Hz. The tone at 28 Hz is shown to be associated with the azimuthal advection of the flame by the outer recirculation zone flow. Changes in the fuel composition, by adding hydrogen (up to 20%), do not affect the correspondence between the thermo-acoustic modes and the flame macrostructures, but shift the transition points to lower equivalence ratio.

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1. Introduction

Self-induced thermo-acoustic instabilities in low NO_x lean premixed combustors remain a significant challenge. Under certain conditions, heat release from the reacting flow couples with the natural frequencies of the combustor to form a positive feedback loop, and produces large sound pressure levels as well as potential flashback. Several comprehensive reviews of the state of the art and the challenges pertaining to combustion instabilities have appeared [1,2], and more recently by Huang et al. [3] who focused on swirl-stabilized combustion, commonly used for flame anchoring in modern gas turbines. Many heat release-acoustics coupling pathways and driving mechanisms have been suggested including flame-vortex interactions and composition or equivalence ratio oscillations. Ducruix et al. [4] describes the different processes and driving mechanisms leading to combustion instabilities. It is well established that combustion dynamics in swirl-stabilized combustors are affected by several variables like the equivalence ratio, inlet temperature and other flow properties like the swirl and Reynolds numbers [5–7]. The fuel composition has also been identified as an important variable affecting the dynamic response [8,9]. In swirl-stabilized combustion, the reacting flow exhibits several flame configurations, what we call flame macro-scale structures or macrostructures. These have been previously reported as a function of fuel composition [10], equivalence ratio and preheat temperature [11,12] and more recently as a function of Reynolds number [13]. Flame macrostructure was also reported to change when some combustor design parameters like the swirler centerbody geometry [14] or the fuel injection staging factor [15] are modified.

It has been suggested that combustion instability in swirl-stabilized combustors is associated with a change in the flame position and shape, or macrostructure [8,11]. In this paper, we investigate this link in more detail. This work comes as a natural extension of the work of Speth et al. [8,16] in which the classical Rayleigh criterion was evaluated for different dynamic modes and a similarity parameter capturing the flame response to flow oscillations for different fuel compositions was proposed; Shroll et al. [17] who explored the dynamic stability characteristics of oxy-combustion; LaBry et al. [18,19] where microjet air injection has been successfully used to suppress thermo-acoustic instabilities. We document the different flame macrostructures under acoustically coupled conditions and their close similarities to those observed under acoustically uncoupled conditions; how the transitions between the different configurations occur at similar equivalence ratio in both cases and the link between these transitions and the changes in the dynamic modes of the combustion including the onset of thermo-acoustic instability; the role of fuel composition in determining the equivalence ratio at which the transitions among the different configurations occur; and the interesting link between ORZ flame flickering in the uncoupled case and the onset of combustion instability in the coupled case, at similar equivalence ratio.

This paper is organized as follows: we first present the experimental set-up, the diagnostics techniques, as well as the approach we followed. Next, we analyze the dynamic stability map of the combustor using pure methane and draw the correspondence with the changes in the flame macrostructure as the equivalence ratio is raised. Changing the combustor length without affecting the underlying flow allows the decoupling of the acoustics over an equivalence ratio range of interest. A comparison of the long coupled case and the short uncoupled case is performed. Then, we analyze in more detail the flame transition from macrostructure III to IV. Finally, fuel composition effect, via H_2 addition, on dynamic modes and flame configurations is investigated.

2. Experimental set-up, diagnostics and approach

2.1. Experimental set-up and diagnostics

Experiments are conducted in a laboratory scale, atmospheric pressure swirl-stabilized dump combustor. Figure 1 shows the detail of the experimental setup, the long combustor, as well as its modification to a short combustor as we will describe in Section 2.2. The fuel, methane and hydrogen at 0%, 10% and 20% volume fraction, and air are premixed upstream of a choke plate.

After the choke plate the mixture flows through a cylindrical pipe with inner diameter $D_{inlet} = 38$ mm and length $L_{inlet} = 14.2 \times D_{inlet}$. The Reynolds number based on the inlet diameter is kept constant at $Re_{D_{in}} = 20,000$. An axial eight-vane swirler with a streamlined centerbody and 45° vane angle placed at a distance $L_{swirler} = 11.6 \times D_{inlet}$ downstream of the choke plate is used to provide the flow with an azimuthal component before entering the combustion chamber. The estimated swirl number is $S = 0.7$. Next, the flow passes through a sudden expansion from