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Symmetry-breaking for the control of combustion instabilities of two interacting swirl-stabilized flames

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ABSTRACT

The concept of 'symmetry breaking' for the control of self-excited combustion dynamics is experimentally investigated in a lean-premixed, swirl-stabilized, two-nozzle, model gas turbine combustor. The present experimental investigation considers two fundamental asymmetries that are rarely explored in tandem – non-uniform fuel split and non-symmetric mean flow field. The equivalence ratio of each nozzle is varied between 0.57 and 0.73, including even and uneven fuel split conditions, and the structure of the mean flow field is altered by means of the swirl numbers of each nozzle, either $S_1 = S_2$ or $S_1 \neq S_2$, representing symmetric and non-symmetric mean flow structures, respectively. The bifurcation behavior of the system is then examined, with particular emphasis on the contributions of flame–flame and nozzle–flame interactions. A non-uniform fuel split is found to have a substantial effect on the system's stability, for both symmetric and non-symmetric mean flame structures, but the stability maps differ remarkably. In the symmetric mean flow, the instability occurs in one region near the even split line. In the non-symmetric case, on the other hand, the unstable region is divided into two regions with considerably lower amplitudes. There is a limit to the asymmetry-induced stability gain, since the instability occurs over a broader region in the stability map considered in the present investigation. The experimental data presented in this paper will help to resolve uncertainties associated with flame interactions in the description of self-excited instabilities.

1. Introduction

Combustion chambers with multiple flames are frequently encountered in practical gas turbine combustion systems. In fact, the operability of gas turbine combustors, including combustion dynamics, flame stabilization, lean blowout, and pollutant emissions, is heavily dependent on flame interaction mechanisms. The interactions are generally governed by several parameters, including fuel staging, swirl number, fuel injection location, the separation distance between adjacent nozzles, the area expansion ratio, and fuel injector impedance. The interplay of these parameters among the nozzles is responsible for the stability and operability of the whole system. Some of the parameters are fixed in the combustor design and construction, whereas parameters such as fuel staging schemes can be actively manipulated even during engine operations. Managing fuel split conditions to simultaneously control combustion dynamics and emissions is an important consideration in the development of gas turbine engines with can-annular combustion systems, or in aeroderivative gas turbine engines with multiple-annular combustion systems. The fundamental mechanism of this control method is to alter local flame properties, which are dominated by the mutual interactions of multiple flame fronts [1].

Due to the complexities associated with strong interactions between neighboring flames, simple extrapolation of the physics of a single axisymmetric flame to the multi-nozzle environment is not recommended, even if exactly identical nozzles are used. The flame dynamics in the presence of an adjacent flame front can be fundamentally different from those of a single flame [2–11]. This discrepancy is particularly pronounced for multi-nozzle can-annular combustion systems [12]. For example, Samarasinghe et al. [13] investigated the effect of fuel staging on the self-excited instability characteristics of a lean-premixed multi-nozzle can combustor. They reported that injecting additional fuel to the middle nozzle of the four-around-one configuration is a very effective method of controlling the instabilities through phase cancellation between adjacent flames. A series of experimental studies on the nature of two interacting lean-premixed non-swirling flames has

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shown that flame front merging in the interaction region reduces the amplitude at which nonlinear flame response occurs [14,15]. This behavior is explained by flame surface density measurements, which demonstrate that jet merging alters the flame–vortex interactions, which are a strong function of flame separation distance. This research was extended to a full-annular configuration to understand the dynamics of azimuthal combustion instabilities [16,17]. Large-scale interactions between adjacent flames in annular configurations were also investigated using numerical combustion simulations [18,19]. Recent studies on the unsteady flow dynamics of single- and multi-nozzle configurations suggest that the unsteady flow fields that develop in response to transverse acoustic excitation are comparable, despite differences in time-averaged flow fields [20,21]. Fanaca et al. [22] performed a similar study, and found that the flow field of a single nozzle configuration is characterized by a larger spreading angle and a higher reverse flow velocity than an annular combustion chamber.

Despite recent advances [23–25], however, an accurate description of the behavior of the system when subjected to multiple flame oscillations is still elusive. Without proper knowledge of the compound effects, we can only speculate on the impact of flame–flame interactions. Here we address this critical issue by examining the limit cycle oscillations of two interacting, lean-premixed, swirl-stabilized flames. In particular, we consider two different types of asymmetry, that is, a non-uniform fuel split between adjacent nozzles and a non-symmetric mean flow field in the transverse direction. The first symmetry-breaking concept is achieved by varying the local equivalence ratio of each nozzle independently, producing a range of split conditions, even and uneven, over a range of global equivalence ratios. A 2-dimensional stability map is then constructed, to visualize the global patterns of the system's sensitivity and the effectiveness of the fuel staging scheme. This method is explored for both symmetric and non-symmetric mean flow structures, with non-symmetric mean flow being the second symmetry-breaking method.

Figure 1 illustrates schematically the interaction of adjacent flames at (a) symmetric and (b) non-symmetric base flow states. In symmetric flow fields, the merging of co-rotating swirling streams occurs in the middle of the combustion chamber. As a result, the inner and outer flame fronts develop symmetrically about the centerline. In this case, asymmetry is caused only by changing the fuel flowrate in the two fuel circuits. By contrast, in Fig. 1b, the base flow field itself is asymmetric. Additional asymmetry is introduced through fuel staging. The response of the two adjacent non-symmetric flames to uneven fuel distributions is expected to be quite different from that of the symmetric case. The resulting effects on the naturally occurring instabilities of the whole reaction zone are systematically analyzed to assess the influence of the two symmetry-breaking methods. Note that these design concepts are often utilized, but in an empirical manner, in real gas turbine engines with multi-nozzle can combustion systems [12].

The objectives of this paper are (i) to quantitatively describe the system's sensitivity to the compound effects of the two types of asymmetries, (ii) to explore the possible causes of system-level changes in association with adjacent flame interactions, and (iii) to explain the most pronounced effects of multi-nozzle configurations in comparison with the single nozzle flame. In the next section, the experimental facilities, operating conditions, and measurement methods, along with their uncertainties, are described. The results of extensive self-excited instability measurements are then presented for both the symmetric and non-symmetric cases. The influence of asymmetry present in the system on the initiation and perpetuation of self-excited instabilities is discussed, through systematic interpretation of the interactions between velocity disturbances and the constituent flames' heat release fluctuations.

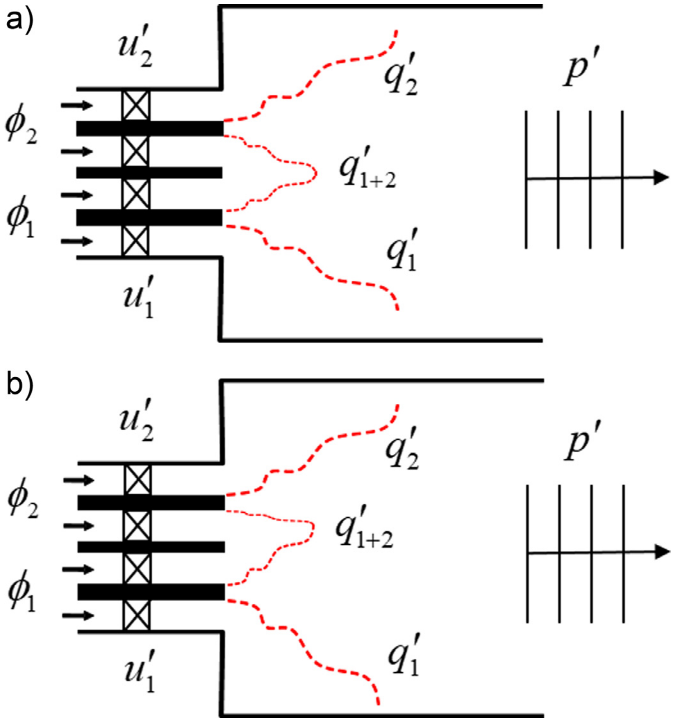

Fig. 1. Illustration of flame–flame interactions for (a) symmetric and (b) non-symmetric mean flow conditions. Subscripts 1 and 2 denote nozzle/flame indices. ϕ_i = equivalence ratio, S_i = swirl number, u'_i = acousticvelocityfluctuation, q'_i = heat release rate fluctuation, p' = acoustic pressure oscillation.

2. Experimental method

2.1. Lean-premixed multi-nozzle gas turbine combustor

Figure 2 shows a lean-premixed, model gas turbine combustor, equipped with two fuel nozzles. This rig was specially designed to study the impact of flame–flame interactions under either forced- or self-excited oscillations. The geometry of the nozzles is identical to that of a single nozzle test rig that was presented in previous publications [7,26], so the data measured using the two test rigs can be compared.

Preheated air enters two separately-controlled fuel nozzles, which are 0.333 m long and have an annular cross-section with a 19.1 mm outer diameter centerbody and a 38.1 mm inner diameter mixing tube. The flow is choked at the entrance of the mixing section, which provides a well-defined acoustic boundary condition. Fuel used is 99.9% CH_4, which is injected far upstream of the choked inlet to create fully-premixed fuel/air mixtures. A six-vane, counter-clockwise axial swirler with swirl number of 0.45 is mounted in each nozzle 76.2 mm upstream of the combustor dump plane, providing the primary flame stabilization mechanism. This swirl configuration, $S_1 = S_2 = 0.45$, yields the symmetric mean flow/flame structure, which serves as a baseline condition. An asymmetric flow structure is also generated by changing the swirl number of Nozzle 1 from 0.45 to 0.75, while the swirl number of Nozzle 2 remains unchanged at 0.45. The ensuing effects of the asymmetric flame interactions are investigated in comparison with the symmetric case. For both symmetric and asymmetric flow conditions, the co-rotating swirl flame dynamics are taken into account here. The effects of different combinations of swirl rotational direction, co-rotating or counter-rotating, are discussed elsewhere [27–29]. Note that even though in this paper the flames with the same swirl number are referred to as symmetric cases, the flow