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Dynamics of premixed swirl flames under the influence of transverse acoustic fluctuations

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ABSTRACT

Flame dynamics in the presence of transverse acoustic fluctuations is an aspect of relevance to modern annular combustors. In particular, it is a key element underlying the occurrence and characteristics of thermoacoustic instability in annular combustors, which primarily involves azimuthal acoustic modes. In this paper, we present our experimental investigation of the response of a generic swirl-stabilized premixed flame to various transverse acoustic forcing configurations. Experiments were performed on a single burner rig featuring a combustor with transverse extensions. The flame was subjected to transverse acoustic fluctuations by generating controlled standing acoustic modes in this combustor. Two main results constitute this study: First, the obtained results reveal that flame response to transverse acoustic pressure fluctuations is quantitatively different when compared to axial forcing for low frequencies. Second, transverse acoustic velocity affects flame response to axial forcing such that the effects are dependent on the amplitude of transverse velocity fluctuations, the phase difference between axial and transverse forcing, and the inherent asymmetry of the flame.

1. Introduction

The response of *premixed flames* to acoustic and hydrodynamic fluctuations is a phenomenon of significant academic interest and technological importance. Heat release rate fluctuations arising from confined unsteady premixed flames act as a source of acoustic energy for the resonant acoustic modes of the confinement (the combustion chamber) [1] and can lead to thermoacoustic instability; The inherent property of the flame to respond to fluctuations thus becomes a determining factor for the stability of the combustor and system components associated with it. The occurrence of the instability leads to operational issues, safety concerns, and restrictions in the operation envelope [2]. Notably, for lean combustion, where significant reduction in emissions can be achieved, the flame response to acoustics is higher when compared to fuel-rich combustion. This results in an increased susceptibility of the system to the instability in this regime. For reliable stability assessment of combustors and for efficient control of the instability, characterization of the flame response and understanding the physical mechanisms that influence flame dynamics are indispensable pursuits.

Previous studies have enabled the identification and details of key mechanisms that govern flame response. As is typically the case in technical combustor configurations such as dump combustors and combustors utilizing swirl flames, flame stabilization is achieved with the help of shear layers, which are also susceptible to acoustic fluctuations [3]. Accordingly, in addition to the direct response to the acoustic field [4,5], the response of such flames is influenced by the dynamics of forced shear layers—specifically by the development of vortical fluctuations generated in response to acoustic forcing [6]. In swirl-stabilized flames, the precessing vortex core might also contribute to coherent flame fluctuations and thus cause instability [7]. Other factors relevant to the response of technical flames that have been identified recently include swirl intensity fluctuations [8–10] and axial vorticity fluctuations [11] resulting from transverse velocity fluctuations generated at the swirler vanes due to acoustic waves impinging on the vanes. These fluctuations are hydrodynamic structures that convect with the mean flow. The reason behind the large impetus behind flame response studies is that the information obtained can be used for reliable and fast prediction of instabilities through efficient methods such as network modeling of the thermoacoustic systems [12], where the system is subdivided into acoustic subsystems and solved for the stability characteristics; The flame is also treated as a subsystem [12,13] and is characterized solely by its response (the flame transfer function, FTF). Such an approach provides the possibility of predicting linear and, to a certain ex-

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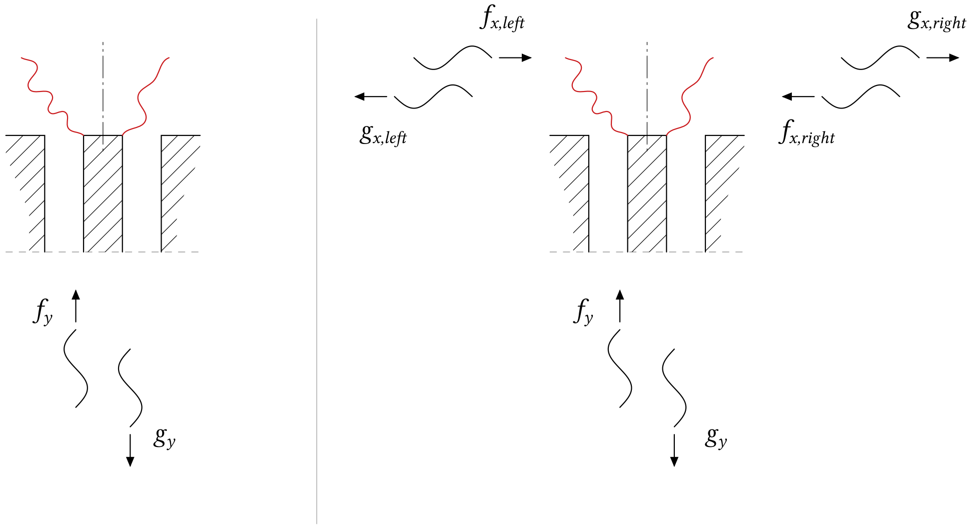

Fig. 1. Schematic illustrating the fundamental difference between a flame under the influence of axial planar acoustics (represented by counter-propagating disturbances, f and g) aligned with the burner axis, and a flame under the influence of simultaneous axial and transverse planar acoustics. The former scenario is typical in longitudinal combustors while the latter occurs in annular combustors. Investigating the influence of transverse acoustics is the focus of this study.

tent, the nonlinear dynamics of the instability [14,15]. Clearly, as a critical requirement for the obtained results to be accurate, the flame response and factors that influence it need to be appropriately accounted for. Consequently, ongoing research on flame dynamics and thermoacoustics constitutes further investigations on the details of flame response mechanisms [16]; nonlinear interactions among physical processes that lead to instability amplitude saturation and subsequent bifurcations [17–21]; and the stochastic dynamics of the thermoacoustic system [22–24] as some of the central themes.

It is important to note that previous research on flame response is predominantly based on assumption that the axis of propagation of incident fluctuation fields is aligned with the axis of the flame. This configuration is schematically shown in Fig. 1(left panel). The assumption has been largely valid as till recently, acoustic modes associated with low frequency thermoacoustic instability would be strictly planar, longitudinal acoustic modes such that the axis of propagation coincides with the burner axis. The immediate question whether results and models that assume flame response to result only from longitudinal acoustics still hold true if the acoustic field is two or three dimensional was previously of little relevance, but has recently gained importance with the advent of annular combustors.

In annular combustors, acoustic modes that establish during instability are predominantly azimuthal acoustic modes such that acoustic fluctuations are transverse to the burner axis—as opposed to being axially-aligned. Detailed discussions on the dynamics of thermoacoustic instabilities in such combustors, particularly the spinning/standing nature of the azimuthal acoustic modes can be found in several recent reports on self-excited instability in industrial and academic annular combustor configurations [25–29]. Flames in annular combustors are subjected to fluctuations in acoustic pressure and velocity that are transverse to the burner axis (Fig. 1, right panel). Additionally, plenum acoustics can lead to axial fluctuations as well. Thus, the assumption of a one-dimensional axial acoustic field that forms the basis of most results on flame response cannot be said to hold true by default for flames in annular combustors.

To investigate the features of the disturbance field and associated flame surface fluctuations induced by transverse forcing, several experimental studies were recently undertaken on single burner test rigs that simulate a sector of an annular combustor [30–33] (See Ref. [34] for a recent review). O'Connor and Lieuwen [31,35] investigated the response of a swirl flame for varying amplitudes of planar high frequency (400, 800, and 1200 Hz) transverse pressure node and antinode forcing. Investigations were largely focused on the development and evolution of flow structures at reacting and non-reacting conditions. It was identified that, similar to the case of a longitudinally forced flow, the fluctuation field of a transversally forced swirl flow is comprised of vortical and acoustic fluctuations in the near field of the burner exit and of acoustic fluctuations further downstream. Transverse forcing was also identified to have an influence on the composition of the vortex breakdown region, based on which the authors argue that transverse forcing—specifically transverse acoustic velocity—will affect the mean flow and flame features, and thereby affect flame response indirectly. Quantification of the flame response through flame transfer function determination for transverse pressure and velocity antinode forcing was undertaken in Ref. [36]. The inferences that could be derived from results obtained were limited to the identification of a non-trivial response in the burner and consequently the flame at the investigated high frequencies.

Baillot and Lespinasse [32] investigated the dynamics of a rod-stabilized V-flame and corresponding base jet flow to high frequency (510, 700, and 1010 Hz) transverse pressure antinode. As in other studies, the authors noted the similarity between flow and flame response to axial and to transverse pressure antinode forcing. The authors focused their efforts to the characterization of vortex dynamics generated in response to transverse acoustic pressure. Interesting vortex interaction mechanisms that would potentially impact flame response were identified.

In general, previous studies provide qualitative evidence to the following features of the flame response were presented:

a. Transverse pressure fluctuations induce axial velocity fluctuations in the burner, which in turn lead to flame response.
b. Transverse velocity fluctuations lead to an anti-symmetric flame response, which does not contribute to a global flame response; unless either the flame itself is asymmetric and the flame surface fluctuations in response to transverse acoustic velocity are not strictly anti-symmetric [37] or nonlinear effects arising from interaction among helical modes, as noted in a recent analytical study [38].