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An experimental investigation of an acoustically excited laminar premixed flame

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Abstract

A two-dimensional laminar premixed flame is stabilized over a burner in a confined duct and is subjected to external acoustic forcing from the downstream end. The equivalence ratio of the flame is 0.7. The flame is stabilized in the central slot of a three-slotted burner. The strength of the shear layer of the cold reactive mixture through the central slot is controlled by the flow rate of cold nitrogen gas through the side slots. The frequency range of acoustic excitation is 400–1200 Hz, and the amplitude levels are such that the acoustic velocity is less than the mean flow velocity of the reactants. Time-averaged chemiluminescence images of the perturbed flame front display time-mean changes as compared to the unperturbed flame shape at certain excitation frequencies. Prominent changes to the flame front are in the form of stretching or shrinkage, asymmetric development of its shape, increased/preferential lift-off of one or both of the stabilization points of the flame, and nearly random three-dimensional fluctuations over large time scales under some conditions. The oscillations of the shear layer and the response of the confined jet of the hot products to the acoustic forcing, such as asymmetric flow development and jet spreading, are found to be responsible for the observed mean changes in the flame shape. A distinct low-frequency component (∼60–90 Hz) relative to the excitation frequency is observed in the fluctuations of the chemiluminescent intensity in the flame under most conditions. It is observed that fluctuations in the flame area predominantly contribute to the origin of the low-frequency component. This is primarily due to the rollup of vortices and the generation of enthalpy waves at the burner lip. Both of these processes are excited at the externally imposed acoustic time scale, but convect/propagate downstream at the flow time scale, which is much larger.

Keywords: Laminar premixed flame; Acoustic response; Chemiluminescence; Confined jets; Combustion instability

1. Introduction

The response of flames to acoustic oscillations is the most crucial aspect of combustion instability in combustors of air-breathing engines such as gas turbines, afterburners, and ramjets. The fluctuating rate of heat release from the flame, influenced by the feedback from the acoustic oscillations, is the source of acoustic driving under conditions of combustion instability. Candel [1] notes that the problem has been investigated from two different approaches, namely, one where the effect of the combustion zone on the acoustic field in the combustor duct is studied, and one where the response of a flame to externally im-

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posed acoustic oscillations is examined. Ducruix et al. [2] have listed several mechanisms of the latter type, including interaction of flames with boundaries, flame–vortex interaction, and interaction of flames with acoustic waves, unsteady strain rates, and equivalence ratio fluctuations. Ducruix et al. [3] have reported theoretical and experimental determinations of the transfer function of a laminar premixed flame. In this work, the temporal fluctuations in the rate of chemical heat release are recorded in terms of the CH^* chemiluminescence of the flame by a photomultiplier tube to experimentally obtain the transfer function of heat release rate response to the imposed velocity fluctuations. More recently, Schuller et al. [4] have also reported velocity field measurements in flames along with flame front imaging over a complete cycle of excitation by conditional sampling and averaging, to study flame dynamics. Schuller et al. [5] have also investigated the self-induced oscillations of a laminar premixed flame stabilized on an annular burner due to the reflection of the acoustic oscillations excited by the heat release fluctuation in the flame at the burner.

Putnam [6] has pointed out that the fluctuations in the flame area within a cycle of acoustic oscillations contribute predominantly to the fluctuations in the rate of heat release. Kaskan [7] noted that variation in the flame area was the primary source of fluctuating rate of heat release when compared to variations in the normal burning velocity of the flame in self-induced quarter-wave resonance modes of a ducted flame system. Based on this, most modeling works on premixed flame dynamics attempt to calculate the fluctuations in the flame area in response to imposed velocity and/or equivalence ratio fluctuations. Fleifil et al. [8] developed a linearized kinematic model for the response of a premixed flame stabilized in a duct in a Poiseuille mean flow subjected to spatially uniform or nonuniform fluctuating flow. They showed the importance of the flame Strouhal number based on the frequency of fluctuation, the duct radius, and the flame speed relative to the reactants. They also showed that the response of the flame area fluctuations to the flow oscillations diminished with increase in frequency. Dowling [9] adopted this framework for a center-body stabilized flame in a duct and relaxed the boundary condition that the flame should be fixed to the edge of the center body when the flow speed dropped below the flame speed. This led to hysteresis and consequent nonlinear behavior of the flame's oscillatory response. Ducruix et al. [3] also adopted this framework to obtain the flame transfer function, which they compared with their experimental data. While the magnitude of the transfer function was reasonably predicted, the prediction of the phase was not as good, particularly for high frequencies. In a unified model for both conical and V-flame stabilized on a center body, Schuller et al. [10] examined the effect of the spatial nonuniformity due to the convective effect of the imposed velocity perturbations particularly prominent at high frequencies in comparison to the flame length-scale. They also reported the results of numerical integration of the nonlinear equation for flame kinematics, as in [4]. They showed that besides the flame Strouhal number, the flame angle to the flow given by the ratio of the flame speed to the mean flow velocity also controlled the flame kinematics; the two parameters could be combined into a reduced frequency of oscillations. The flame kinematics approach has also been adopted for examining the effect of equivalence ratio fluctuations by Hubbard and Dowling [11] and Cho and Lieuwen [12]. Lieuwen [13] has comprehensively reviewed the modeling efforts on interaction of acoustic oscillations with premixed flames recently.

An aspect of all kinematic models mentioned above that is pertinent to the present work is that the flame is assumed to be attached to the rim of the burner or the flameholder without undergoing any oscillations (with partial exception of [9]). Besides fluctuations at the point of attachment of the flame to the burner rim or the flameholder, the flame also exhibits other interesting features not adequately captured in the models, such as excitation of frequencies different than that externally imposed, or shifts in the mean position about which the flame fluctuates. Bourehla and Baillot [14] performed experiments on an open premixed flame stabilized on a round orifice and excited from upstream in the frequency range of 20–1000 Hz. They observed a wide range of qualitative behavior in the response of the flame, which they mapped in the domain of excitation frequency versus the amplitude of velocity fluctuations nondimensionalized by the laminar flame speed. These observations include flame wrinkling, filtering, tilting, subharmonic excitation, wrinkling/subharmonic transition, and collapsing, and chaotic and hemispherical appearance under different conditions. The filtering occurs in the 200–600 Hz range, causing a large hump centered around 86 Hz to appear in the spectrum of the flame's response. The tilting is observed in the low frequency–high amplitude range. The work focuses further on wrinkled, subharmonic, and chaotic flames, the first two restricted in appearance to frequencies below $\sim$220 Hz. The subharmonic flame oscillates at half the excitation frequency in either symmetric or asymmetric fashion. The chaotic flame occurs for high-amplitude excitation in the 100–600 Hz range. Durox et al. [15,16] studied the collapsed and hemispherical flames exhibited at high amplitudes of excitation in the high-frequency range ($>$600 Hz). A significant change in the mean shape of the flame from being conical to hemispherical or bulb-shaped is