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Hydrodynamic instability and shear layer effect on the response of an acoustically excited laminar premixed flame

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ABSTRACT

Combustion instabilities can cause serious problems which limit the operating envelope of low-emission lean premixed combustion systems. Predicting the onset of combustion instability requires a description of the unsteady heat release driving the instability, i.e., the heat release response transfer function of the system. This study focuses on the analysis of fully coupled two-way interactions between a disturbance field and a laminar premixed flame that incorporates gas expansion effects by solving the conservation equations of a compressible fluid. Results of the minimum and maximum flame front deflections are presented to underline the impact of the hydrodynamic instability on the flame and the shear layer effect on the initial flame front wrinkling which is increased at decreasing gas expansion. These phenomena influence the magnitude of the burning area and burning area rate response of the flame at lower frequency excitation more drastically than reduced-order model (ROM) predictions even for low temperature ratios. It is shown that the general trend of the flame response magnitudes can be well captured at higher frequency excitation, where stretch effects are dominant. The phase response is influenced by the DL mechanism, which cannot be captured by the ROM, and by the resulting discrepancy in the flame pocket formation and annihilation process at the flame tip.

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1. Introduction

Combustion instabilities frequently occur in lean premixed gas turbine combustors due to the coupling of the acoustic modes with the unsteady heat release of the flames. This phenomenon can result in high amplitude pressure fluctuations that cause, e.g. excessive pollutant emissions or even hardware damage [38]. Thus, a key requirement for the prediction of the onset and evolution of these instabilities is a model for the response of a premixed flame to velocity fluctuations generated by acoustic waves. There have been significant efforts from various groups over the past decades which have developed analytical solutions for the transfer function of the heat release rate of the flame and the imposed acoustic velocity fluctuation [7,9,13,36,43,44,50]. These analyses, however, neglected the influence of gas expansion at the flame surface on the flame surface motion, since analytic solutions for the flame transfer function are not available. The experiments of Birbaud et al. [3] and Karimi et al. [29] showed that gas expansion has a significant influence on the characteristics of the premixed flame transfer function for ducted flames. Preetham et al. [43] argued from computations of a ducted premixed flame including the effect of gas expansion effects that these differences in transfer function characteristics can be qualitatively explained by mean flow acceleration induced by gas expansion in the presence of a duct. First, the effective transit time of flame wrinkles from the base of the flame to the tip is reduced and second, the change in the effective perturbation velocity amplitude at the flame surface is accounted for. Birbaud et al. [2] performed velocity measurements in the upstream region of a conical Bunsen flame and showed that the flow field in this region is significantly modified due to the presence of the flame. The flow in the unburnt region was observed to be accelerated on cusped regions of the flame surface and decelerated in regions between separating alternate cusps. Birbaud et al. [3] and Hemchandra [26,27] observed similar features in the upstream region of the flame from computations performed in the context of flame response to equivalence ratio perturbations. This alternating pattern of accelerated and decelerated flow causes the amplitude of flame surface perturbations to increase. Recently, Cuquel et al. [6] analyzed confined flames by the reduced frequency ω_*^c which is a function of the confinement

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ratio C_r and the gas expansion ratio T_b/T_u. This is the first theoretical attempt to analyze the effect of confinement and gas expansion on the flame transfer function and is also valid for multiple flame set-ups that were previously analyzed [8,11,32,33]. They showed that the flame transfer function of confined flames matches that of an unconfined flame below the critical reduced frequency $\omega_*^c < 3\pi$ and stated that additional parameters should be included in the analysis to match the flame transfer functions in the higher frequency range. These differences in the high frequency range are possibly due to the neglected flame stretch and gas expansion effects that not only cause the gas to expand but also result in a preferential acceleration of the flame front perturbations due to the convective Darrieus–Landau instability [51]. This instability might explain the differences in their analysis for the high confinement ratio $C_r = 0.81$, where the flame height normalized by the reference diameter is increased by 1 compared to the height of an unconfined flame with the flame height of $L_f = 3$. Since the balance of the flame front curvature effects and increasing flame front perturbation is missing in the analysis in [6] these differences probably occur for high confinement ratios. In further studies Shin et al. [53,54] analyzed the flame wrinkle destruction process for a bluff body stabilized flame due to kinematic restoration and flame stretch. They found that the flame wrinkle destruction process can be separated into four regions (1) negligible flame wrinkle destruction, (2) flame stretch controlled wrinkle destruction, (3) kinematic restoration controlled destruction, and (4) dissipated flame wrinkles. Furthermore, they showed that the decay rate of the flame wrinkles in the second and third region is a function of the harmonic content in the excitation signal, of the Markstein length, the downstream position and the excitation amplitude. The experimental and analytical modeling studies of Searby et al. [51] led to the argument that when flame wrinkles travel from the flame base to the flame tip the amplification of flame surface perturbations is due to the influence of the convective DL instability. The DL instability is caused by the preferential acceleration of the flow normal to the flame surface in regions that are concavely curved relative to upstream reactants and vice versa, resulting in an increased amplitude of the flame surface perturbation [34,46]. This results in a temporal instability for freely propagating premixed flames of infinite extent and in a convective instability for attached premixed flames with a large upstream flow component tangential to the flame surface [51]. In the latter case an increased overall flame surface area oscillation is observed that influences the heat release response characteristics. The growth of these flame surface perturbations, however, is significantly influenced by the modification of the flame speed due to flame front curvature. For reactant mixtures, where the flame speed increases when the flame front curvature becomes more negative, the growth rate of flame wrinkles begins to reduce at decreasing wave number. Beyond a given critical value the flame becomes stable, hence perturbations are damped. Therefore, a wave number, at which the flame is neutrally stable, exists for a given temperature ratio and reactant mixture Markstein length [34,46]. Thus, a large change in the characteristics of the heat release transfer function is expected when the associated flame surface perturbation changes from being unstable to stable. In addition to the convective DL instability the flame wrinkling evolution is influenced by the disturbance field which introduces a change in the vorticity distribution depending on the gas expansion ratio, the curved streamlines, and the varying flame front position [12,25,37,39,52]. Thus, the fully coupled two-way interaction between the disturbance field and the flame determines how the flame wrinkles develop when traveling from the flame base to the tip [37,39,52–54].

In this study the conservation equations of a compressible fluid are solved for a two-dimensional slot-stabilized premixed flame for different burnt to unburnt gas temperature ratios of $1 \leqslant T_b/T_u \leqslant 7$ to analyze the increasing gas expansion effects and the influence of the vortices generated in the shear layer near the flame base on the flame response characteristics. These computational results are compared with corresponding flame front and flame heat release response characteristics determined by the reduced-order modeling (ROM) approach for premixed flame heat release response [55]. The Markstein length and the perturbation wave number induced on the flame surface are varied as well as the reduced-order model to understand the differences in the response characteristics of flames that are caused by the convective DL instability and the vorticity field. The objective of this analysis is to show how gas expansion effects influence the dynamics of a flame perturbed by convecting vortical disturbances and to indicate the limits of the reduced-order modeling that cannot capture the impact of the convective Darrieus–Landau instability caused by the presence of gas expansion and the shear layer effect on the flame response. The paper will identify parameter ranges where these effects influence the flame response significantly such that they cannot be neglected in future reduced-order modeling studies. The flame front kinematics is analyzed over a wide range of temperature ratios and Markstein lengths to emphasize the impact of the flame front deflection, flame pocket formation, separation, and annihilation on the overall flame response. Especially, the last three types of dynamics at the flame tip are analyzed in detail to show that these key features cannot be predicted well in the reduced-order modeling when the balance of the radial upstream velocity field induced by gas expansion to the flame stretch becomes significant. The results of the flame front analysis can be used as a reference solution to develop an analytic reduced-order model that includes the gas expansion. Although the influence of confinement on the flame response cannot be neglected [6,43], this effect is not analyzed in the present paper. We will focus on the influence of the confinement ratio on the coupled two-way interactions between disturbance field and the flame in a future study.

The paper is organized as follows. The flame transfer function to analyze the flame response characteristics of an acoustically excited laminar premixed flame is defined in Section 2. Section 3 provides details of the simulations based on the two-dimensional conservation equations of a compressible fluid for a perturbed flat flame to investigate the DL instability and an acoustically excited premixed flame. Section 4 summarizes details of the reduced-order model formulations of the acoustically excited premixed flame. Subsequently, the results are discussed in Sections 5 and conclusions are drawn in Section 6.

2. Flame transfer function

The instantaneous heat release rate $q(t)$ from the flame normalized by the mean heat release rate q_0, can be written as

$$\frac{q(t)}{q_0} = \frac{\int_{\chi_f} s_{L,u} dA}{\int_{\chi_f} \bar{s}_L dA_0}, \tag{1}$$

where the integral is computed at the flame front χ_f, A_0 is the mean flame surface area of the acoustically excited flame and $s_{L,u}$ is the flame speed relative to the unburnt reactants (Fig. 1). The time dependent quantities in the numerator on the right-hand side (RHS) in Eq. (1) can be written as perturbations about their respective mean values as $dA = dA_0 + dA'$ and $s_{L,u} = \bar{s}_L + s'_L(t)$ which yields

$$\frac{q'(t)}{q_0} = \frac{\int_{\chi_f} s'_{L,u}(t) dA}{\int_{\chi_f} \bar{s}_L dA_0} + \frac{A'(t)}{A_0}. \tag{2}$$

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