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EFFECTS OF NONUNIFORM REACTANT STOICHIOMETRY ON COMBUSTION INSTABILITY

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ABSTRACT

This paper analyzes the forced response of swirl-stabilized lean-premixed flames to acoustic forcing in a laboratory-scale stratified burner. The double-swirler, double-channel annular burner was specially designed to generate acoustic velocity oscillations and radial fuel stratification at the inlet of the combustion chamber. Temporal oscillations of equivalence ratio along the axial direction are dissipated over a long distance, and therefore the effects of time-varying fuel/air ratio on the flame response are not considered. Simultaneous measurements of inlet velocity and heat release rate oscillations were made using a hot wire anemometer and photomultiplier tubes with narrow-band OH*/CH* interference filters. Time-averaged CH* chemiluminescence intensities were measured using an intensified CCD camera. Results show that flame stabilization mechanisms vary depending on stratification ratio for a constant global equivalence ratio. For a uniformly premixed condition, an enveloped M-shaped flame is observed. For stratified conditions, however, a dihedral V-flame and a detached flame are developed for outer stream and inner stream fuel enrichment cases, respectively. Flame transfer function (FTF) measurement results indicate that a V-shaped flame tends to damp incident flow oscillations, while a detached flame acts as a strong amplifier relative to the uniformly premixed condition. The phase difference of FTF increases in the presence of stratification. More importantly, the dynamic characteristics obtained from the forced stratified flame measurements are well correlated with unsteady flame behavior under limit-cycle pressure oscillations. The results presented in this paper provide insight into the impact of nonuniform reactant stoichiometry on combustion instabilities, which has not been well explored to date.

1. INTRODUCTION

In spite of extensive research efforts over the last two decades, combustion instabilities remain a major challenge for the development of advanced gas turbine engines. A primary obstacle is the difficulty in developing generalized flame response models which are capable of capturing the underlying physicochemical phenomena as well as providing frequency- and amplitude-dependent transfer function information. Accurate prediction of the flame response is a difficult problem, because the unsteady heat release oscillation is influenced by numerous factors. Understanding how a flame responds to different types of upstream disturbance of varying amplitude and frequency is therefore crucial for the development of reliable flame response models. The availability of such models is essential for the design of advanced combustion systems [1].

The major types of disturbance of interest in gas turbine engine development include acoustic velocity oscillation [2-4], equivalence ratio oscillation [5-8], entropy fluctuation [9-10], pressure oscillation [11-12], and temporal oscillation of swirl strength [13-14]. In highly turbulent gas turbine engine environments, acoustic velocity and equivalence ratio fluctuations are generally regarded as the dominant perturbations [15]. Acoustic velocity oscillations are propagated into the combustion chamber at the speed of sound. Equivalence ratio fluctuations are, however, convected by the mean flow. The two types of oscillation thus have different propagation mechanisms and consequently, their rates of dissipation are orders of magnitude different. Most previous studies on linear/nonlinear flame transfer functions have focused on the response of laminar/turbulent premixed flames to either inlet velocity oscillations [2-4] or equivalence ratio oscillations [5-8] for different burner geometries.

The two types of perturbation have until now generally been treated separately, to reduce the complexity of measurements and interpretations. It has been well documented that the interactions between a flame and flow structures with a broad range of length scales play an important role in determining the flame response. In particular, the interaction of a flame and a coherent large-scale structure is an important mechanism for nonlinear response [2, 16-17]. Temporal oscillations of mixture ratio nonuniformities have also been identified as a nonlinearity mechanism, and are associated with the intrinsically nonlinear dependence of the heat of reaction and burning velocity on the equivalence ratio [8, 18].

The aforementioned investigations on the dynamic response of a flame subjected to a single perturbation, either acoustic velocity or equivalence ratio perturbations, can be extended to explore the forced response of a partially premixed flame to the combined actions of both types of perturbation. Recently, Kim et al. [19] investigated the constructive and destructive interference of inlet velocity and equivalence ratio oscillations in the mixing plenum, and showed that the response of a partially premixed flame is amplified or damped depending on the phase relationship between the two temporal oscillations. The concept of a two-input one-output system was recently introduced by Huber and Polifke [20] to model partially premixed flame transfer functions. They calculated the response of a partially premixed flame using two flame transfer functions obtained by numerical simulation of the transient fluid dynamics of a turbulent reacting flow. The concept was experimentally demonstrated in a highly turbulent environment and its physical significance was discussed in Ref. [21]. In real gas turbine injectors, however, combustion takes place under spatially nonuniform stoichiometry. These spatially-nonuniform reactant streams complicate the problem.

The impact of nonuniform reactant stoichiometry (fuel stratification) has been investigated experimentally [22-25] and numerically [26-29]. Several distinct features have been reported. First, it has been found that heat release rate is significantly increased by stratification at globally fuel-lean conditions, because of the different burning velocities of leaner and richer regions to create additional flame surface area [22-23, 27-28]. The impact of stratification at fuel-lean conditions is also related to the history effect: flame propagation is back-supported by heat and radicals resulting from combustion that has occurred at a higher equivalence ratio [27, 29]. Second, it is known that stratification has a significant effect on such local flame structures as curvature, flame brush thickness, and flame surface density [30]. Third, stratification helps lean flammability limits extend into the much leaner range [23]. Furthermore, flame structure and stabilization mechanisms of a stratified swirl flame are heavily influenced by fuel distribution [25]. Recent experimental investigations by Meier et al. [31] showed that partially premixed conditions have a significant effect on the internal scalar structures and geometric properties of partially premixed swirling CH_4/air flames.

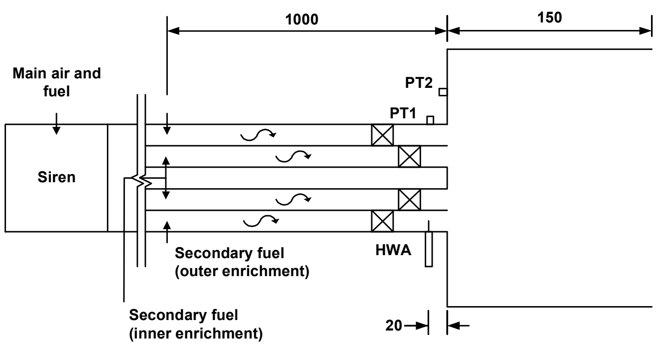


Figure 1. Schematic of a stratified swirl burner. Dimensions in millimeters. Not to scale. ($D_{c.b.}$ = 6.35, $D_{i.t.}$ = 15.05, $D_{o.t.}$ = 27.75, $D_{q.t.}$ = 94.00 mm).

There have been few systematic investigations of the influence of stratification on lean-premixed turbulent swirl-stabilized flames in a gas-turbine-relevant environment. The present investigation is an extension of prior work [19], in which the effect of temporal equivalence ratio oscillations was taken into account, along with acoustic velocity oscillations. In the present paper, the spatial distribution of fuel/air ratio at the combustor inlet is considered and its impact on the response of the flame to acoustic velocity oscillation is emphasized. The principal findings of the present research will help improve our understanding of the dynamic properties of turbulent stratified swirl flames in a model gas turbine burner.

This article begins with details of experimental facilities, operating conditions, and measurement techniques. Results of measurements are described and interpreted in Section 3. The bifurcation of flame structure according to inlet fuel/air stratification is addressed. The linear response of partially premixed flames is discussed in comparison with the response of uniformly premixed flames. Experimental measurements of limit-cycle pressure oscillations for premixed and stratified conditions reveal key physical processes controlling the unsteady dynamics.

2. EXPERIMENTAL METHODS

2.1 Stratified swirl burner

An axisymmetric, laboratory-scale, lean-premixed burner was used in this investigation. It is illustrated schematically in Fig. 1. This burner consists of an air inlet section, a siren, a mixing section, an optically-accessible quartz combustor section, and an exhaust section. Air is introduced and mixed with the fuel (methane) flow far upstream of the mixing plenum for the uniformly premixed cases. To introduce velocity oscillation at the inlet of the combustion chamber, a siren-type modulation device with a rotating plate and a stator is used. The siren is driven by a variable-speed AC motor (EZ motor Model 55EZB500), which is controlled by a Control Techniques Epsilon 203 driver (Model Eb-203-00-C01). The siren provides capabilities for changing the forcing frequency up to 660 Hz. A ball valve is used to control the amount of air/fuel mixture that bypasses the siren, thereby allowing the amplitude of the inlet velocity fluctuation to be varied independently. The mixing plenum is 1000 mm long (inner diameter = 27.75 mm). It consists of a concentric inner tube and a centerbody. The centerbody has a diameter of 6.35 mm and the inner tube has an outer diameter of 15.05 mm (thickness = 1.5 mm). The centerbody and the inner tube are centered in the mixing tube, and positioned such that their downstream ends are flush with the combustor dump plane. For stratified conditions, additional fuel is injected into the inner or outer streams to create nonuniform stoichiometry in the radial direction. The additional fuel injection takes place 1000 mm upstream of the combustion chamber entrance. It was found in Ref. [19, 21] that the temporal (or axial) oscillation of equivalence ratio is completely dissipated when the ratio of diffusion time to convection time (τ_D/τ_c) is approximately 190 in a turbulent flow field. In the present burner configuration, the ratio of two time scales is 170. Therefore, the temporal oscillation of equivalence ratio along the axis can be assumed to disperse before the perturbation impinges on the flame front. Accordingly, temporally homogeneous reactant mixtures enter the combustion chamber (spatial non-homogeneity is caused by confinement). To further enhance fuel/air mixing, two axial swirlers, which each have six swirl vanes and 45° swirl angles, are mounted in the injector.

The combustor consists of a stainless steel dump plane block and an optically accessible fused-silica section with an inner diameter of 94.0 mm and length of 150.0 mm. For forced flame response measurements, the combustor length was held at 150 mm to reduce the influence of the system's acoustics on upstream forcing. At this condition, the resonance frequency of the system is an order of magnitude higher than the forcing frequency and thus the resonant effects are minimized. For measurements of self-excited instabilities, a longer quartz tube with a length of 800 mm was used. The exit of the combustor is at ambient conditions. Detailed dimensions are included in Fig. 1.

2.2 Instrumentation and test conditions

Pressure oscillations were measured with Model 40GP GRAS pressure transducers in the mixing section and the combustor section. A hot film probe (Dantec, Model 55P11) controlled by a constant temperature anemometer (CTA) bridge (Mini CTA 54T30, Dantec) was used to measure inlet velocity fluctuations. The calibrated CTA was located 20 mm upstream of the combustor dump plane, and oriented perpendicular to the inlet flow. Two photomultiplier tubes (PMT, Thorlabs model PMM01) coupled with narrow bandpass interference filters were used to measure the global OH* (307 ± 5 nm) and CH* (432 ± 5 nm) chemiluminescence emission intensities from the whole flame. It was ensured that the image of the flame was correctly cast on the cathodes of the PMTs. It was also verified that the measured PMT output signal was linear with respect to light emission intensity from the whole flame over the entire range of operating conditions. It was found that for a given equivalence ratio distribution, the relative perturbation in power, and thus heat release rate, is approximated as proportional to the change in chemiluminescence intensity. Therefore, the ratio of the fluctuating to mean chemiluminescence can be considered to be proportional to the fluctuation in heat release. Note that temporal effects of equivalence ratio are not externally imposed here. If temporal oscillations of equivalence ratio in the injector occurred or if the local equivalence ratio of one stream were higher than stoichiometric condition (ϕ=1.0), quantitative interpretation of the chemiluminescence-based method would be difficult in estimating accurate transfer functions.

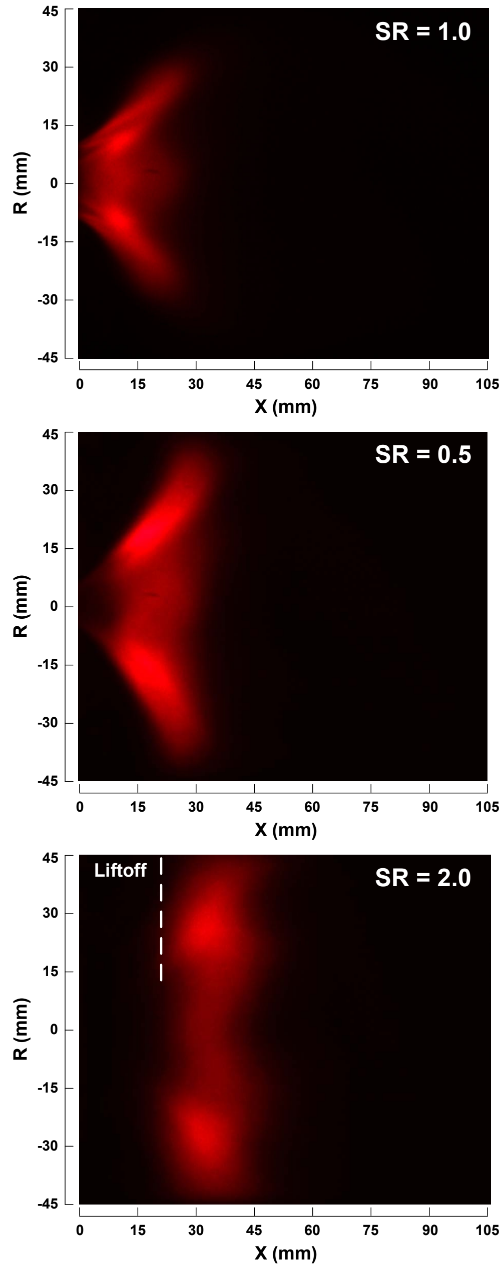


Figure 2. Time-averaged CH* chemiluminescence images for different stratification ratios. X = 0.0 indicates the entrance of the combustion chamber. Inlet conditions: p_i = 1 atm, T_i = 20 °C, U = 5 m/s, ϕ_g = 0.60, $SR = \phi_i/\phi_o$ = 0.5, 1.0, 2.0.

A LaVision Imager Intense CCD camera (1376 × 1040 pixel) equipped with a gated intensifier (gain = 80%) and a Nikkor UV AIS 105 mm *f*/4.5 objective was used to acquire spatial distributions of the CH* chemiluminescence signal. A narrow wavelength interference filter centered at 430 nm (10 nm FWHM) was mounted to record direct light emission, line-of-sight integrated images. For time-averaged flame image measurements, 200 individual images were accumulated for an exposure time of 600 μsec. A background image was subtracted from the raw images to correct for noise. Care should be taken when spontaneous emission from CH in the electronically excited state are used to analyze quantitatively heat release distribution [32]. The PMTs and the ICCD camera were focused on the same combustion zone.

Experimental data were recorded with a National Instruments data acquisition system controlled by the Labview software program at a sampling frequency of 8192 Hz. A total of 16,384 data points were taken during each test, resulting in a frequency resolution of 0.5 Hz and a time resolution of 0.122 msec. Spectral analysis of the signals was performed using a fast Fourier transform (FFT) technique. All tests were performed at the ambient pressure and temperature condition. Mean velocity in the injector was 5 m/s and the global equivalence ratio was varied from 0.50 to 0.60. All measurements were made at globally fuel-lean conditions. The stratification ratio, SR, defined as the ratio of the inner stream equivalence ratio to the outer stream equivalence ratio, was varied by keeping the air flow rate constant while varying the fuel flow split between the inner and outer tubes. The input power was thus unchanged for a constant global equivalence ratio. Forcing frequencies were varied between 60 and 400 Hz in 20 Hz steps, and the forcing amplitude was kept constant at u'/U = 5% to ensure the linear response. The amplitude dependence of the flame response is not described in the present work.

3. RESULTS AND DISCUSSION

In this section, several distinct features of lean-premixed, stratified flames are interpreted in terms of a comparison with the corresponding homogeneous condition. First, the structure and stabilization mechanisms of premixed and stratified flames are discussed. Second, flame transfer functions for different fuel split ratios are presented, and the impact of nonuniform reactant stoichiometry on limit cycle oscillations is discussed based on time- and frequency-domain analysis.

3.1 Stabilization mechanisms of stratified lean premixed flames

Time-averaged CH* chemiluminescence images for stratification ratios SR = 0.5, 1.0, 2.0 are shown in Fig. 2. The global equivalence ratio is constant, ϕ_g = 0.60; only fuel distribution is varied. For the baseline condition, SR = 1.0, the inner and outer stream have the same equivalence ratio. Figure 2 shows, first of all, that an enveloped M-shaped flame is developed when SR = 1.0. The uniformly premixed flame is compact and the swirl flame is stabilized at the edge of the centerbody as well as at the rim of the inner tube. When SR = 0.5, the flame structure is similar to a dihedral V geometry. The stratified flame with outer stream enrichment is attached to the edge of the centerbody. The primary reaction region is located in the shear layer induced by the centerbody. The other flame branch, which is stabilized in the inner tube shear layer at SR = 1.0, is blown off. For SR = 2.0, the stratified swirl flame is anchored at a finite distance away from the combustor dump plane. The intense reaction occurs in the downstream region, where the interaction of the flame and the combustor wall is significant. At the inlet conditions considered here, three different flame configurations are observed for the three stratification ratios, at a constant global equivalence ratio. A similar phenomenon was observed by Nogenmyr et al. [25] in a study on stabilization of turbulent lean premixed and stratified flames. They described three different shapes of flame front: a single V-shape tilted towards one side of the burner, and W-shape, and multiple V-shape fronts. The modification of flame stabilization process is expected to cause substantially different flow and scalar fields inside the combustor, leading to a significant change in the unsteady flame dynamics subjected to acoustic forcing. This will be shown in the next section.

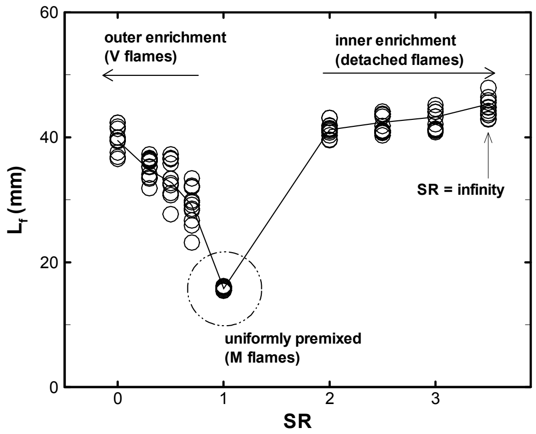


Figure 3. Influence of the stratification ratio on effective flame length. Inlet conditions: p_i = 1 atm, T_i = 20 °C, U = 5 m/s, ϕ_g = 0.50, 0.55, 0.60, $SR = \phi_i/\phi_o$ = 0.0, 0.3, 0.5, 0.7, 1.0, 2.0, 2.5, 3.0, ∞.

To quantitatively describe the bifurcation of the flame, time-averaged CH* chemiluminescence emission intensity was analyzed to calculate effective flame length ($L_f = L_{CH^*max}$) for premixed and stratified conditions. L_f is defined as the distance between the edge of the centerbody and the maximum CH* chemiluminescence intensity location. The parameter is known as an important length scale in the generalization of the forced response of swirl-stabilized flames [33]. Figure 3 plots the dependence of effective flame length on the stratification ratio at global equivalence ratios, ϕ_g = 0.50−0.60. Stratification ratios were varied between zero and infinity, the two extreme cases in which all fuel is injected through the outer stream and the inner stream, respectively. All the measurements were performed at globally lean conditions. It is evident from Fig. 3 that the effective flame length is smallest for the premixed flames regardless of global equivalence ratio for the conditions tested. The length deviates from the baseline condition as the stratification ratio increases or decreases. The left branch indicates the dihedral V flame regime, while the right branch denotes detached flame regime. The effective flame length increases for both stratified regimes, and the influence is more pronounced as the stratification ratio approaches zero or infinity. The detached flames exhibit the longest effective flame length, followed in decreasing order by outer mixture enrichment cases and uniformly premixed cases. This result is related to the phase difference of FTF (convection time scales), which will be discussed later.

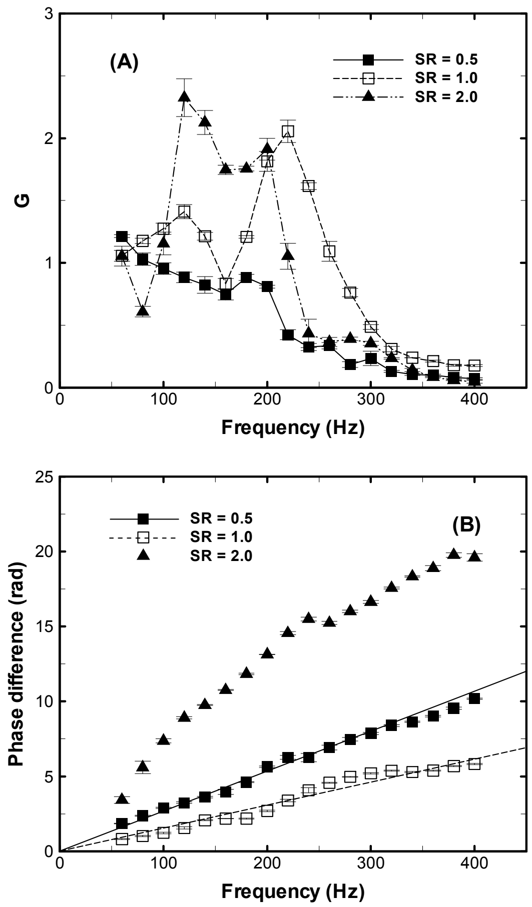


Figure 4. Linear response: (A) flame transfer function gain and (B) phase difference as a function of forcing frequency for different fuel split ratios. Error bars represent rms deviation. Inlet conditions: p_i = 1 atm, T_i = 20 °C, U = 5 m/s, ϕ_g = 0.60, $SR = \phi_i / \phi_o$ = 0.5, 1.0, 2.0.

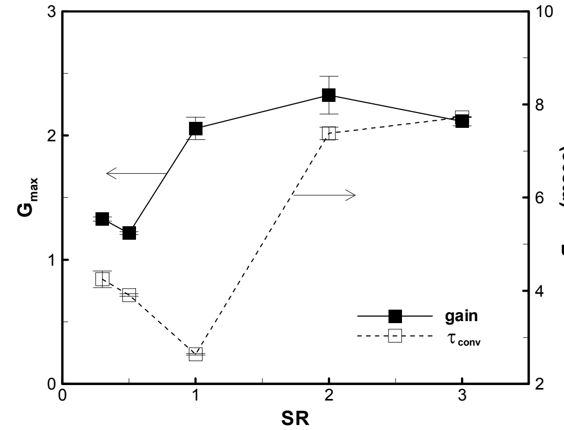


Figure 5. Convection time and maximum gain vs. stratification ratio.

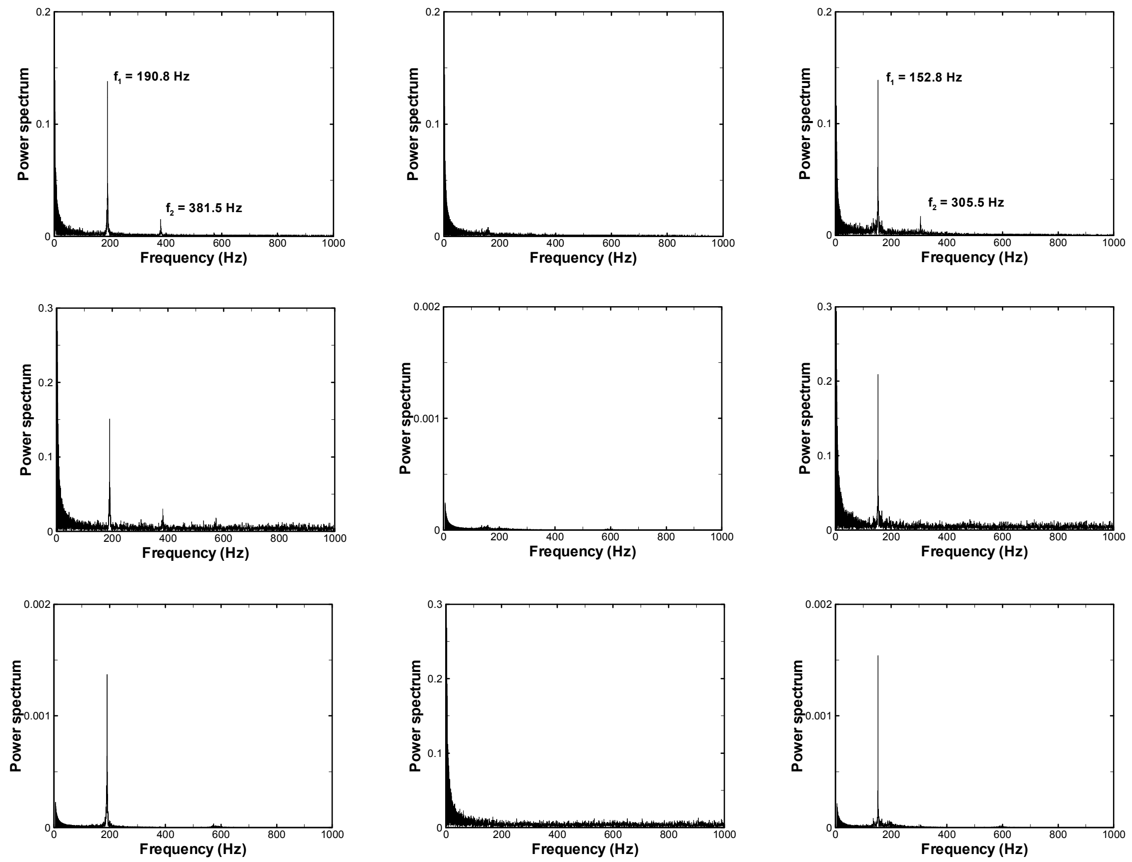
3.2 Forced flame response measurements

The dynamic flame response to acoustic forcing is mathematically described by flame transfer functions, which are defined by the ratio of heat release rate to inlet velocity oscillation, where both are normalized by their corresponding time-averaged values:

$$FTF(f)\big|_{\phi(r_0)} = \frac{Q'(f)/\overline{Q}}{u'(f)/U} \qquad (1)$$

where u' and Q' are the Fourier components of inlet velocity and heat release rate oscillations at a given forcing frequency, respectively. The subscript $\phi(r_0)$ denotes the spatial dependence of equivalence ratio at the base. Flame transfer functions were determined for different fuel split conditions. The global equivalence ratio is kept constant; that is, the total air and fuel flow rates are unchanged. Velocity (u') measurements using a constant temperature anemometer at the entrance of the combustion chamber confirmed that the normalized magnitude of inlet velocity fluctuation in the inner and outer streams are within 5%. This measurement indicates that the physical confinement does not affect the magnitude of velocity oscillation at the entrance of the combustion chamber and therefore the influence of nonuniform distribution of $u'(f)/U$ along the flame front can be eliminated from the transfer function analysis.

Figure 4 shows the flame transfer function gain and phase difference as a function of forcing frequency for different stratification ratios. The evolution of the gain and phase of the FTF suggests that, firstly, in the case of outer stream enrichment (SR = 0.5), the gain is close to unity from 60 Hz to 100 Hz. Beyond 100 Hz, the FTF gain drops smoothly down to zero. No strong peaks above unity are observed. The phase difference between u' and Q' increases almost monotonically with frequency from 60 to 400 Hz. Second, for the premixed



(A) SR = 1.0 (B) SR = 0.5 (C) SR = 2.0

Figure 6. Power spectra of OH* chemiluminescence intensity (top), inlet velocity (middle), and combustor pressure (bottom) for different stratification ratios, SR = 1.0, 0.5, 2.0 under limit-cycle oscillations, for a combustor length of 800 mm. Inlet conditions: p_i = 1 atm, T_i = 20 °C, U = 5 m/s, ϕ_g = 0.60.

condition (SR = 1.0), the gain is larger than that of the inverted V flame at a constant forcing frequency, and two distinct peaks are seen at 120 Hz and 220 Hz. The phase increases almost linearly with frequency. The premixed condition shows the smallest phase difference and SR = 2.0 the largest. The influence of stratified reactant streams on the phase difference of the FTF is well correlated with the effective flame length, as illustrated in Fig. 3. The larger the effective flame length, the larger the convection time. Third, for the detached flame (SR = 2.0), the gain exceeds unity for a range of forcing frequencies between 100 Hz and 220 Hz, indicating that this flame geometry is more sensitive to incident perturbations. The amplification of the FTF of swirl-stabilized flames may be related to an interaction between the flame and the combustor wall boundary [34]. This issue is left for future studies.

The effects of stratification on the forced flame response are summarized in Fig. 5, in terms of maximum gain values and convection time delays. The latter can be calculated from the slope of FTF phase difference. In the case of FTF gain, fuel stratification in the direction of the inner and outer stream has an opposite influence. Outer stream enrichment tends to reduce the flame's sensitivity to perturbations, while inner stream enrichment tends to amplify the flame response as compared to the uniformly premixed condition. In contrast, both cases of fuel stratification increase convection time delay with a more pronounced effect in the inner stream enrichment cases. The same trend is also observed for different global equivalence ratios and inlet velocities.

3.3 Measurements of self-excited instabilities

Measurements of self-excited instabilities were made to investigate the influence of radial fuel stratification on the limit-cycle behavior of CH_4/air premixed and partially premixed flames. Long quartz tubes of different lengths (400, 600, 800, 1000 mm) were used to modify eigenfrequencies of the combustion system. Strong limit-cycle oscillations were observed only for L_c = 800 mm at the operating conditions considered here.

The typical power spectra of OH* chemiluminescence, inlet velocity, and combustor pressure at limit cycle oscillations are shown in Fig.6. The frequency-domain result exhibits several distinct features, as follows. First, for a uniformly premixed flame, strong limit-cycle oscillations are observed at a frequency 190.8 Hz. The power spectra of OH* chemiluminescence and velocity signals show a distinct peak at the fundamental mode and a weak peak at the second harmonic frequency. On the other hand, the pressure power spectrum exhibits a distinct peak only at a frequency of 190.8 Hz. Second, in contrast to the case of SR = 1.0, the combustor is quite stable when the outer stream is richer than the inner stream. It is believed that the underlying physics is related to variations in flame topology caused by non-homogeneous local equivalence ratio. The effect of flame wrinkling and curvature caused by turbulence and local mixture ratio heterogeneities on finite rate chemistry need to be further investigated. Third, high-amplitude limit cycle oscillations are also observed for SR = 2.0. Detached flames are likely to be susceptible to thermoacoustic instability. The instability occurs at 152.8 Hz, which is different from the limit-cycle frequency of the uniformly premixed condition. The modification of limit cycle oscillation frequency is related to convection time delays estimated by the forced flame response measurement. As illustrated in Fig. 5, the flame with SR = 2.0 has the largest convection time delay, indicating that the flame's characteristic frequency is the smallest among the three cases considered here. This is consistent with the measurement results presented in Fig. 6. Fourth, the measured self-sustained instabilities for both SR = 1.0 and SR = 2.0 correspond to the quarter-wave longitudinal acoustic mode. In the present investigation, the self-excitation is observed to fluctuate slightly for a given tube length. This may reflect the sensitivity to environmental boundary conditions, such as ambient temperature and pressure.

Finally, the measured self-excited instability intensities for different stratification ratios increase with the gain of the flame transfer functions, which show the flame's sensitivity to incident acoustic/convective perturbations. As shown in Fig. 4 (A), the stratified flame with SR = 0.5 tends to damp incident flow oscillations. No amplification behavior is seen. The V-shaped flame does not show well-organized limit-cycle oscillations, as shown in Fig. 6. On the other hand, Fig. 4 (A) clearly shows that the flames at the other conditions, SR = 1.0 and SR = 2.0, strongly amplify upstream flow disturbances in the frequency range of 120 Hz − 220 Hz, which is consistent with the unsteady flame behavior under limit-cycle oscillations. The interpretation described here shows how physical properties obtained from the forced flame response measurements can be utilized to analyze self-excited instability phenomena.

To suppress the intensity of combustion instability caused by temporal fluctuations of equivalence ratio, passive control methods have been implemented in large-scale gas turbine combustors [35-36]. These investigations were motivated by theoretical and experimental studies on the role of equivalence ratio oscillation on combustion instabilities. The experimental results presented in the present paper demonstrate that the fuel distribution functions in the injector exert a significant influence on self-sustained combustion instability in combustion systems. For the development of quiet low emissions combustion engines, therefore, the spatial dependence of equivalence ratio as well as the temporal dependence must be carefully considered. Furthermore, the interactions of spatio-temporal equivalence ratio variations and acoustic oscillations in the injector must be investigated in further detail.

4. CONCLUSIONS

Thermoacoustic combustion instabilities have been investigated in a model stratified gas turbine burner. The effect of fuel/air ratio inhomogeneities on the forced flame response and self-excited oscillation was systematically studied in a well-controlled test environment. In particular, the correlations between the forced flame behavior and limit-cycle dynamics are highlighted. The following conclusions can be drawn. The structure and stabilization mechanism of turbulent partially premixed stratified flames are heavily influenced by fuel split ratios at the inlet of the combustion chamber. Depending on the radial fuel stratification, the flame shows three different types of flame front: a V-shape attached to the bluff body, an M-shape attached to the bluff body and the inner tube, and a detached flame front. Stratification has a significant effect on the forced flame response to acoustic excitation. The forced response of outer stream enrichment cases is reduced substantially, but the inner stream enrichment results in a strong amplification of the flame response relative to uniformly premixed flames. The FTF phase reaches minimum at SR = 1.0, but it increases for both stratified conditions. Self-excited instability measurements indicate that combustion under stratified conditions, particularly outer stream enrichment, is a useful method for suppressing high-amplitude limit-cycle pressure oscillations in combustion systems.

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