

Effects of hydrogen addition on flame structure and forced flame response to velocity modulation in a turbulent lean premixed combustor

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ABSTRACT

Flame transfer function measurements were performed in a turbulent premixed lean combustor with various blends of hydrogen and natural gas. The fuel mixture was completely premixed with air upstream of a choked inlet to the combustor to avoid equivalence ratio fluctuations. A variable speed siren was used to modulate fluctuations in the inlet velocity, which was measured using a hot wire anemometer as an input parameter of the flame transfer function. Heat release oscillations as an output function were determined using chemiluminescence measurements from whole flames. Stable flame images were captured to understand general flame behavior over a range of operating conditions and fuel blends. Experimental results showed that the stable flames' COMs (centers of mass) laid along a common path in a 2-D plane for all of the operating conditions and tested fuel compositions at a given injector geometry, and that variations in the stable flame shape could be characterized by the location of the common path of the flame's COM. It was also shown that changes in the fuels significantly affected the flame shape; as a result, flame dynamics varied with changes in flame geometry. Accordingly, flames that were close together on the characteristic flame COM curve were shown to have similar forced flame responses.

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1. Introduction

Industrial gas turbines generally operate on natural gas (NG), and lean premixed combustors are adapted for meeting aggressive NO_x emission regulation targets by lowering the flame temperature. However, due to dramatic increases in natural gas prices and strong demand for reduced dependence on fossil fuels, advanced power generation systems such as integrated gasification combined cycle (IGCC) technology are expected to play an important role in future electrical power generation and energy production [1,2]. In an IGCC power plant, coal is gasified to generate synthetic gas (syngas) fuels, which typically contain a significant amount of hydrogen as well as carbon monoxide. Accordingly, chemical kinetics of syngas fuels are directly affected by mixture composition, and in turn, flame and combustion characteristics in IGCC system combustors will be different from those in conventional lean premixed combustors running on natural gas only. This difference provides a major motivation for fundamental research on the effects of fuel flexibility on combustor operability, including flashback, auto-ignition, lean blowout, and combustion instability [3–16].

There has been significant research on the effects of flashback, lean blowout, and auto-ignition. Flashback occurs when the turbulent flame speed exceeds the flow velocity along some streamline, allowing the flame to propagate upstream into the premixing section [4]. Kido et al. [5] and Kitagawa et al. [6] tabulated turbulent flame speeds for various fuel blends. More specifically, Fritz et al. [7,8] performed experimental determinations of flashback limits in a premixed swirl burner and found that a Peclet number model could be applied successfully to correlate flashback limits in their experimental configuration.

Auto-ignition in premixed combustors occurs when premixer conditions are suitable to initiate self-sustaining combustion, although no flames are present downstream [4]. Multiple research groups have documented results on auto-ignition behavior for fuel blends of methane with hydrogen and other hydrocarbon fuels [3,4,9–12].

Fuel flexibility can be an important consideration for combustors operating very close to the lean blowout limit. Previous works on the lean blowout demonstrated that changes in fuel composition were related to change in laminar flame speed [13,14], and lean blowout limits depended on the ratio of chemical kinetic time and residence time [15,16].

One of the biggest issues related to fuel flexibility in the lean premixed combustor is combustion dynamics. Combustion instabilities are characterized by large amplitude pressure oscillations

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which are caused by unsteady heat release from the flames. A combustor enters an unstable state when the unsteady heat release and acoustic pressure oscillations in the combustor are in phase [17,18]. Changes in fuel composition can affect the phase difference between the pressure and heat release fluctuations because variations in fuel properties affect both chemical and convective time delays [3]. Balachandran et al. [19] and Kim et al. [20] showed that transfer function measurements can provide accurate information on the convection time delay in premixed flames. Recently, a number of research groups have been working on flame transfer function measurements to study the coupling between the heat release fluctuation and the velocity and/or equivalence ratio perturbations [19–25]. For premixed flames with no equivalence ratio fluctuations, the flame transfer function describes its dynamic heat release response to inlet flow perturbations as a function of frequency (f); this function can be defined as

$$T(f) = \frac{Q'(f)/Q_{mean}}{V'(f)/V_{mean}} \quad (1)$$

where Q_{mean} is the temporal mean of the heat release rate, V_{mean} is the mean bulk velocity of the mixture entering the combustor, and Q' and V' are their corresponding fluctuating components.

The objective of this work was to experimentally obtain the flame transfer function in a turbulent lean premixed combustor operating on various hydrogen-natural gas mixtures. Specifically, the current study focused on the flame structure impact on the flame's forced response to upstream velocity fluctuations. To accomplish this, chemiluminescence images were taken from whole flames over a range of operating conditions with various fuels. Then the flame transfer function for a perfectly premixed flame was measured in a lab-scale premixed combustor. Lastly, both results were analyzed to find the relationship between the stable flame geometry and the transfer function measurement results.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The experimental setup consisted of an optically accessible fused-silica combustor section (150 mm in diameter and 300 mm in length), a nozzle assembly and a device for modulating inlet velocity, as shown in Fig. 1. The combustor exit was fully open without any restriction. The nozzle assembly consisted of a center-bluff

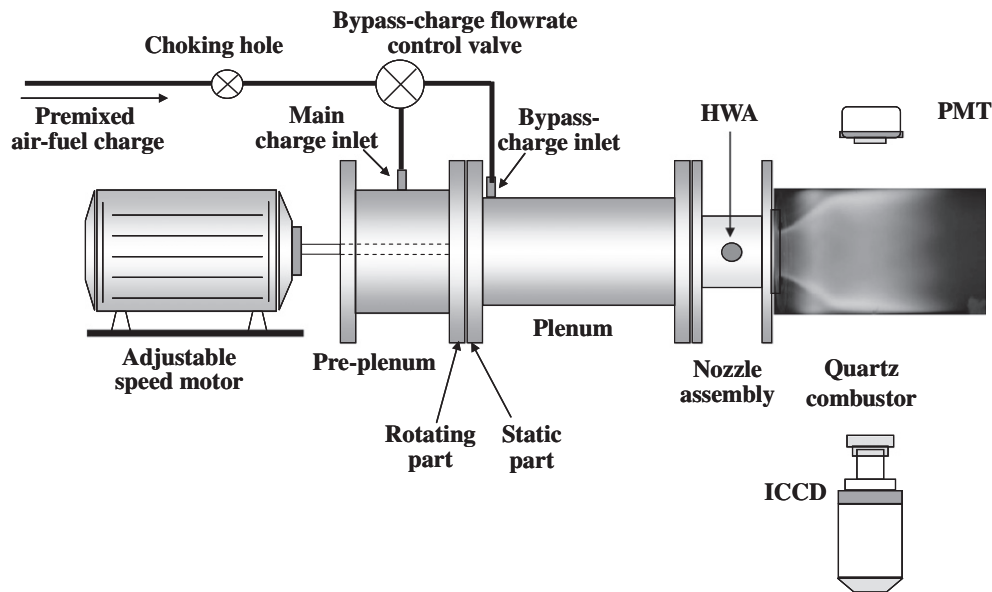


Fig. 1. Schematic diagram of experimental setup.

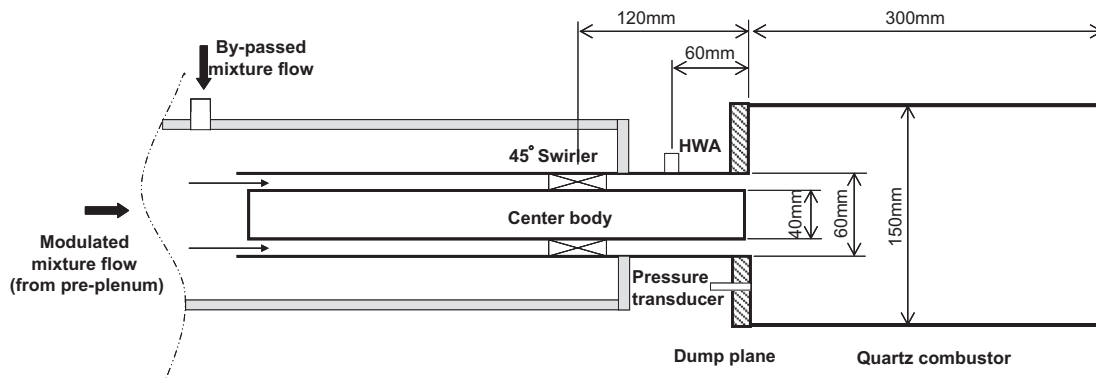


Fig. 2. Schematic drawing of combustor and nozzle-assembly.

body ($D = 40$ mm) whose end face was recessed by 20 mm from the dump plane and an annular mixing section where 45° swirl vanes were located. Fig. 2 shows the schematic drawing of the combustor and nozzle assembly.

For the flame transfer function measurement, a siren type modulation device was used to impose the inlet-velocity fluctuation (V'). It consisted of a variable-speed motor, a rotating plate, a pre-plenum and a stator, and its modulation frequency range extended up to 300 Hz. The amount of inlet-velocity fluctuation (V'/V_{mean}) was varied in order to control the relative amount of air flow through the modulating device. Fuel was completely premixed with air upstream of a choked inlet in order to avoid equivalence ratio fluctuation.

2.2. Measurement

The velocity fluctuation in the annular mixing section was measured using a hot wire anemometer (HWA, TSI model 1210) located 60 mm upstream of the dump plane. Photomultiplier tube (PMT, Hamamatsu model 928A) was used to measure the global OH^* chemiluminescence intensity from the whole flame, which was collected using a narrow band-pass (± 5 nm) filter centered at 307 nm. The calculated values of $(OH^*)/(OH^*)_{mean}$ via the Fast Fourier Transform (FFT) were used as the estimates for the heat release fluctuations. The signals from the HWA and PMTs were digitized and recorded by a digital data acquisition system at a sampling rate of 16,384 Hz. In total, 16,384 data points were sampled during each test.

An ICCD camera (Princeton Instruments model 576G) equipped with a band-pass filter ($\lambda = 307 \pm 5$ nm) was used to capture the OH^* chemiluminescence from the whole flame. For stable flame image measurements, 40 individual images for each case were taken and averaged. For phase-averaged imaging, the camera was

synchronized with the HWA signal, and six averaged images over one period of oscillation were collected with a phase interval of 60° . A three-point Abel deconvolution scheme was used to reconstruct the two-dimensional flame structure [26].

2.3. Test conditions

The test conditions in this work are summarized in Table 1. Measurements were made at the equivalence ratios of 0.65, 0.675, 0.7, 0.725 and 0.75 for the mean mixture velocities of 25–37.5 m/s. For each operating condition, five fuel composition cases (100% NG, 15% H_2 + 85% NG, 25% H_2 + 75% NG, 35% H_2 + 65% NG, 50% H_2 + 50% NG, by volume) were tested. For flame transfer function measurements, inlet mixture velocity was modulated with frequencies ranging from 75 to 280 Hz. The amount of flow modulation (V'/V_{mean}) which was controlled by a bypass valve was fixed at 7% at each frequency for the current test. Tests were conducted at room temperature and atmospheric inlet conditions.

3. Results and discussions

3.1. Overall chemiluminescence intensity measurement from stable flames

Chemiluminescence measurements have been widely used as indicators of heat release rate in combustion research. As presented in the previous work by Nori et al. [27], especially for hydrogen-natural gas flames, OH^* chemiluminescence is considered to be a reasonable choice for the rate of heat release measurement, compared to other species such as CH^* and C_2^* .

Fig. 3 shows the OH^* chemiluminescence intensities as a function of the heat release rate of the total fuel (hydrogen + natural gas) flow rate, as determined by the following equations.

$$HRR_{total} = HRR_{hydrogen} + HRR_{NG} \quad (2)$$

$$HRR_{hydrogen} = \dot{m}_{H_2} \times LHV_{H_2} \quad (3)$$

$$HRR_{NG} = \dot{m}_{NG} \times LHV_{NG} \quad (4)$$

where, HRR : heat release rate, MJ/min, \dot{m}_f : mass fuel flow rate, kg/min LHV : lower heating value, MJ/kg.

For each data point, the results were recorded after the PMT signals were completely stabilized at a given operating condition. The plotted data consists of the averaged values over more than 20 measurements at the same conditions. Measurement was performed under stable conditions for velocities of 25–37.5 m/s at

Table 1

Test conditions.

Mean velocity in the nozzle ($V_{mean, nozzle}$)	25–37.5 m/s
Equivalence ratio (ϕ)	0.65, 0.675, 0.7, 0.725, and 0.75
Fuel composition (hydrogen fraction by volume) (%)	0, 15, 25, 35, and 50
Inlet flow temperature	20 °C
Modulation frequency (f)	75, 100, 140, 200, 250, and 280 Hz
Modulation amplitude (V'/V_{mean}) (%)	7
Reynolds number	29,700–42,500

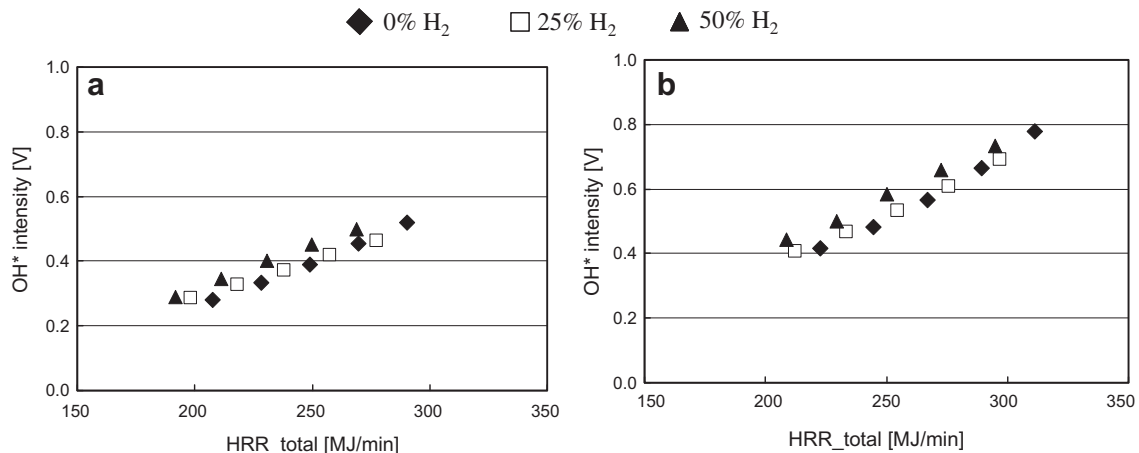


Fig. 3. Overall OH^* chemiluminescence intensity as a function of rate of heat release by total fuel flowrate ((a) $\phi = 0.65$ and (b) $\phi = 0.7$, for stable flames).

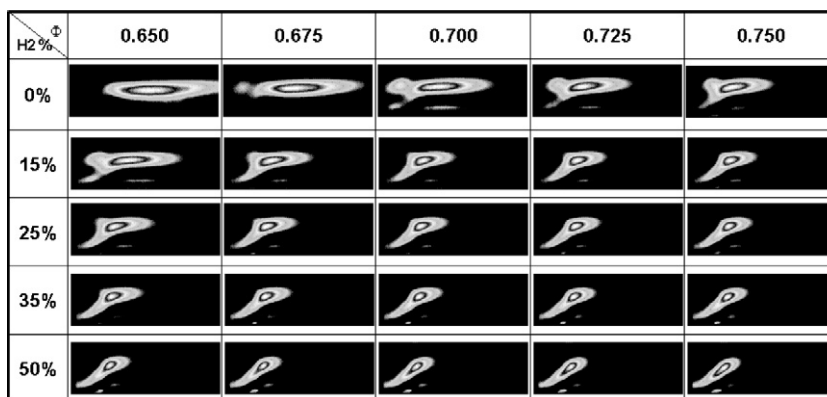


Fig. 4. Deconvoluted OH^* chemiluminescence images under stable conditions for $V_{\text{mean, nozzle}} = 30$ m/s.

equivalence ratios of 0.65 and 0.7 with three different fuel blends. It is generally known that overall chemiluminescence intensities are linearly dependent upon the heat release rate at a given equivalence ratio. As viewed in Fig. 3, the OH^* intensity was mostly independent of changes in fuel composition, which implies that the OH^* chemiluminescence is a good indicator for the heat release rate measurement in the hydrogen-natural gas flames.

3.2. Effect of hydrogen addition on the stable flame structure

OH^* chemiluminescence images were taken under stable conditions for hydrogen-natural gas premixed flames in order to identify the effects of fuel composition on flame structure. For each test condition, the gate width of an ICCD camera was fixed at 0.5 ms, and 40 images were taken and averaged. Here, only the upper half of the flame was introduced because the deconvoluted images were axisymmetric.

Fig. 4 shows the deconvoluted chemiluminescence images of stable flames for five fuel composition cases (100% NG, 15% $\text{H}_2 + 85\%$ NG, 25% $\text{H}_2 + 75\%$ NG, 35% $\text{H}_2 + 65\%$ NG, and 50% $\text{H}_2 + 50\%$ NG) at a nozzle velocity of 30 m/s and equivalence ratios from 0.65 to 0.75. The flame structure was significantly affected by the amount of hydrogen added to the natural gas flame, as well as by the equivalence ratio. As the hydrogen fraction of the fuel mixture increased, the flame length decreased and the location of maximum intensity moved closer to the combustor inlet plane at a given equivalence ratio and air mixture.

For more quantitative analysis on the flame structure, the flame's center of mass (COM) was calculated from each deconvoluted chemiluminescence image and was plotted as a function of equivalence ratio, as shown in Fig. 5. It was evident that the distance of the flame's COM from the dump plane decreased with increasing hydrogen at a given equivalence ratio; this trend was more obvious for the low equivalence ratio cases (i.e., $\phi = 0.65$ or 0.675) than for the high equivalence ratio cases (i.e., $\phi = 0.725$ or 0.75).

It was also interesting to see how the flame's COM changed with variations in operating condition and fuel. Figura et al.[28] found that flame COM locations lay along a common path in a 2-D plane for all test conditions and fuels in their experimental configuration. The same approach was attempted in the present study with the current test nozzle and combustor. Fig. 8 is a plot of the locations of the flames' COMs in a 2-D plane for the entire test conditions studied. As viewed in the plot, the location of the flame's COM moved along a certain "characteristic" curve as the test conditions and fuels were changed. It was also interesting to see that flames having the same center of mass location had very

similar flame structures. This was true for any two adjacent data points on this graph.

Based upon the current results, it is expected that the center of mass path is characterized by injector geometry, and that flames with the same center of mass will have very similar flame shapes.

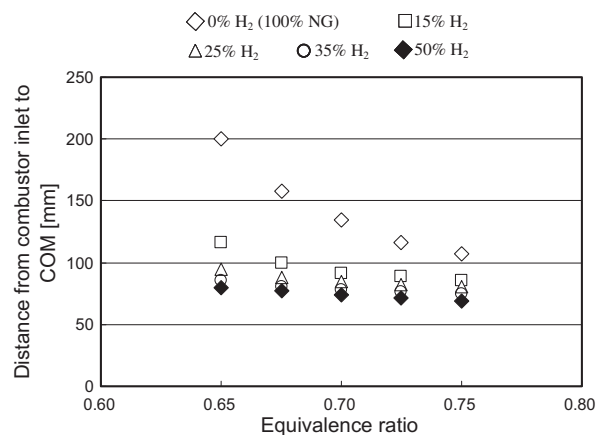


Fig. 5. Distance from combustor inlet to flame's COM as a function of equivalence ratio and fuel composition for $V_{\text{mean, nozzle}} = 30$ m/s.

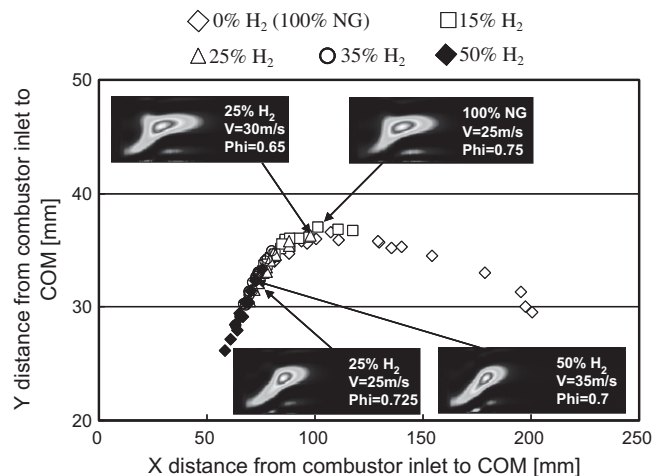


Fig. 6. Location of the flame's COM for $V_{\text{mean, nozzle}} = 25, 30$, and 35 m/s, and $\phi = 0.65$ –0.75, and for five different hydrogen volumetric fraction of 0%, 15%, 25%, 35%, and 50%.

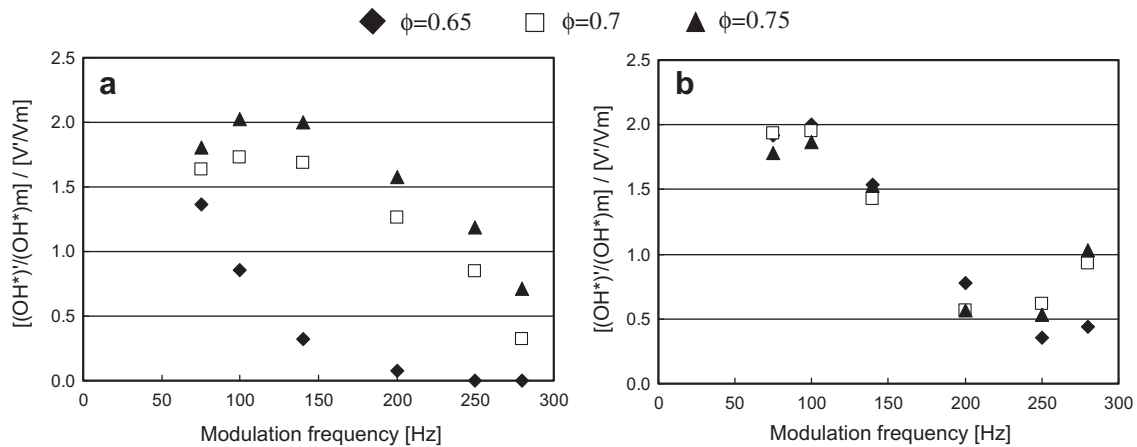


Fig. 7. Gain of transfer function as a function of modulation frequency ((a) 100% NG flame and (b) 25% H₂ + 75% NG flame, $V/V_{mean} = 0.07$, $V_{mean, nozzle} = 30$ m/s).

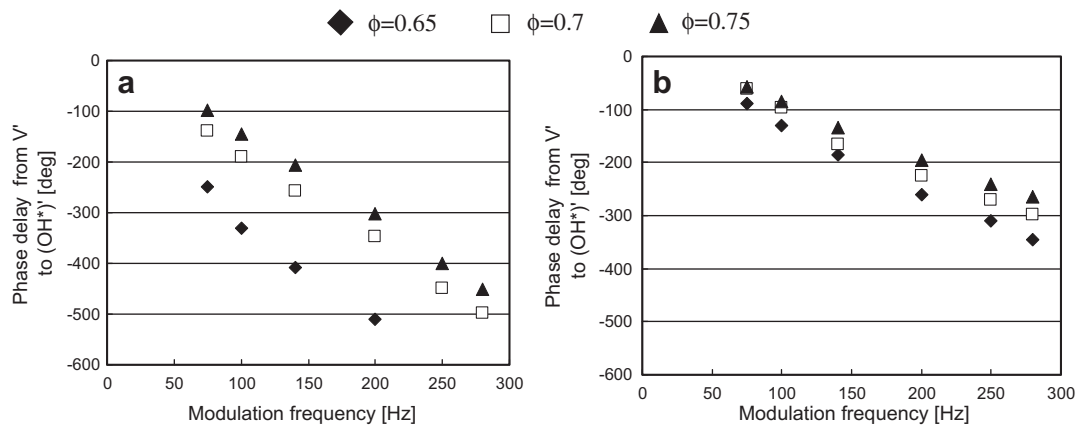


Fig. 8. Phase delay of transfer function as a function of modulation frequency ((a) 100% NG flame and (b) 25% H₂ + 75% NG flame, $V/V_{mean} = 0.07$, $V_{mean, nozzle} = 30$ m/s).

3.3. Flame transfer function measurements for the hydrogen-natural gas mixtures

In order to characterize the forced flame response for a hydrogen-natural gas mixture, the flame transfer function measurements were made for the various fuel blend cases with premixed air/fuel mixtures.

Fig. 7 shows an amplitude comparison for the OH* chemiluminescence fluctuations normalized by the mean value between the 100% natural gas flame and the 25% hydrogen + 75% natural gas flame at a mean velocity of 30 m/s and equivalence ratios of 0.65, 0.7 and 0.75. Here, at each modulation frequency, the amplitude of the velocity fluctuation was fixed at 7% ($V'/V_{mean} = 0.07$), which means that the results represent the gain in the transfer function.

Comparison of the gains shows different behaviors for the two fuel mixtures, although all other operating conditions were identical. For modulation frequencies below 140 Hz, the gains for the two different fuel mixtures showed quite similar behaviors, except at an equivalence ratio of 0.65, in which case the flame with no hydrogen addition was much longer than the flame to which hydrogen had been added (Fig. 4). However, for modulation frequencies above 200 Hz, the gain of the transfer function in the hydrogen-added flame dropped more drastically than did that of the natural gas flame, reaching a low point around 250 Hz and then rebounding.

A possible explanation for the different flame dynamics between the two fuel mixtures is the difference in flame structure.

Candel's research group [21–23] found through a series of flame transfer function measurements that the responses of flames to external flow perturbation strongly depend on flame geometry. Durox et al. [24] and Santosh et al. [25] also presented similar observations, in which flame shape varied with fuel composition, as shown in Fig. 4, resulting in changes in flame dynamics.

Another purpose of transfer function measurements is to determine the phase delay between a velocity fluctuation in the nozzle and the corresponding heat release oscillation in the combustor. The convection time delay (the required time for the inlet velocity perturbation to be convected to the flame) can be calculated using this phase delay [19,20]. Fig. 10 compares the phase delay of the transfer function between the 100% natural gas and the 25% hydrogen + 75% natural gas cases. The absolute values of the phase delays for the natural gas flames were greater than those for the hydrogen-added flames, reflecting the observation that flame length decreased with increasing hydrogen flow rate at a given equivalence ratio, as shown in Figs. 4 and 5.

As shown in Figs. 7 and 8, variations in fuel composition had a great effect on flame dynamics in terms of both the gain and the phase. As previously discussed, this may be due to the difference in flame structure. To verify this explanation, we compared the flame transfer function results between two data points having the same stable flame structure but with different fuel mixtures. Fig. 9 is a plot of the transfer function measurement results for two different fuel composition cases: one was 100% natural gas, $V = 25$ m/s, $\phi = 0.75$; the other was 25% hydrogen, $V = 30$ m/s, $\phi = 0.65$. These two cases were chosen since they showed very

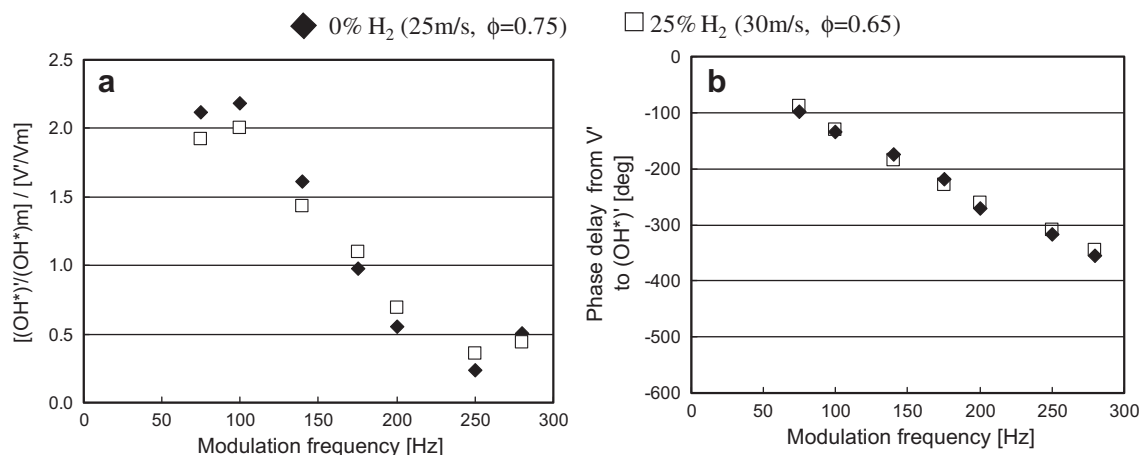


Fig. 9. Comparison of flame transfer function for two data points with the same stable flame's COM location.

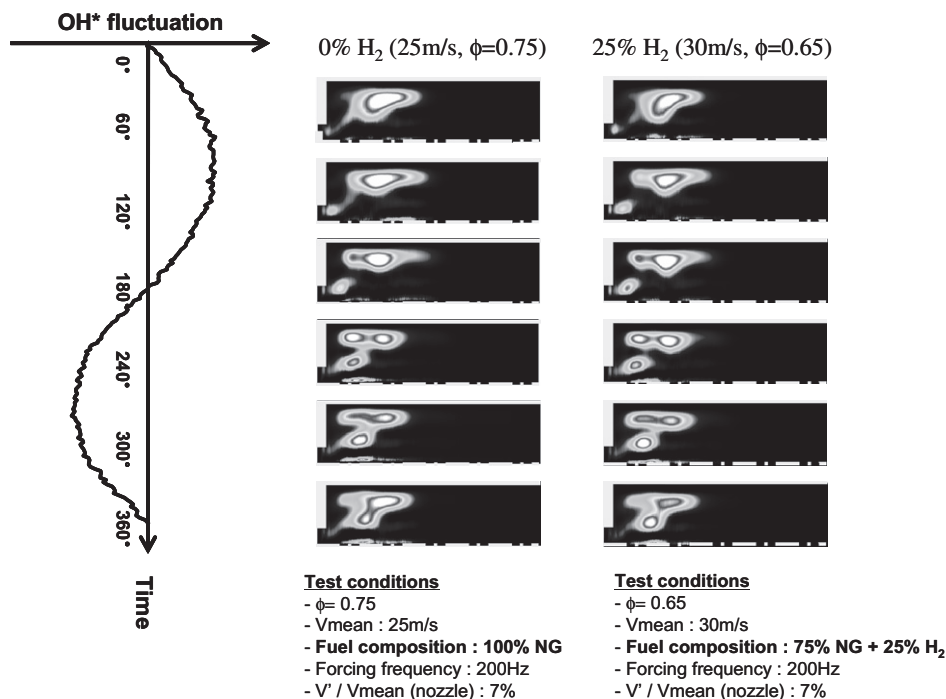


Fig. 10. Comparison of sequential phase-synchronized flame images for two data points with the same stable flame's COM location.

similar stable flame structures and COM locations as introduced in Fig. 6. As seen in the plots, the gain responses as well as the phases behaved very similarly over the measured range of frequencies. This similarity was typical for other pairs of adjacent data points in Fig. 6.

Fig. 10 compares phase-synchronized OH* chemiluminescence images for the 100% natural gas and the 25% hydrogen. In a side-by-side comparison of the images and magnitudes of the inlet-velocity fluctuations, the global characteristics of the flames were found to be very similar; this indicates that a flame's forced response under upstream flow modulation is dependent upon the stable flame shape, even with different fuel compositions.

4. Conclusions

In summary, it was found that changes in fuel composition strongly affect flame geometry, showing that combustion

dynamics depends on the fuel. It is known that the phase delay between heat release and pressure fluctuation can vary with changed in chemical and convection time delays. The results of the flame transfer function can be used to calculate the convection delay time according to fuel composition change and to investigate the phase delay between acoustic pressure and unsteady heat release oscillations in the case of self-excited combustion instability measurements. It was also found that the gain of the transfer function, as well as the phase, changed significantly with variation in the fuel even under the same operating conditions.

It was found that the stable flame COM moves along a characteristic curve with changes in operating condition and fuel, given fixed fuel nozzle and combustor geometries. In addition, flame data points that are close together in the COM curve exhibit very similar flame structures and show very similar forced responses to external flow perturbations.

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