

Measurement of Local Equivalence ratio in Partially Premixed Swirling Methane Flame Using Local Chemiluminescence

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Introduction

Swirling flows have been widely used in industrial burners in order to increase fuel-air mixing and to improve flame stabilization. It has been shown that swirl can increase mixture homogeneity and shorten the characteristic time for NO_x formation and result in lower NO_x emissions [1-3]. However, in non-premixed swirling flames, the reduction of NO_x emissions is generally accompanied by an increase of CO emissions. Recently, the pollutant emissions generated from *partially premixed swirling* methane jet flames were measured to study the effect of partial premixing on EINO_x and EICO and to develop a scaling law for EINO_x [4]. Measurements indicated that minimization of both NO_x and CO emissions can be achieved with an optimum level of partial premixing in swirling flames. Although similar trend of decrease then increase in EINO_x with increasing levels of partial premixing, as that in laminar flames, was observed in partially premixed swirling methane flames, more information such as radical concentration, reaction rate, and local flame stoichiometry are needed to provide further explanation of the behaviors in NO_x emissions. The focus of this work is on the measurements of local equivalence ratio in partially premixed swirling flame using non-intrusive method by observing the naturally occurring, optical emissions from the flame.

It has been shown that the chemiluminescent emissions of OH^* , CH^* , and C_2^* , resulted from electronically excited state, in hydrocarbon flames can be related to chemical reaction rate and heat release rate [5-7]. The ratios of chemiluminescence of CH^*/OH^* and C_2^*/OH^* were used to determine local equivalence ratio in laminar and turbulent flames [8-9], atmospheric pressure micro-gas turbine combustor [10], and swirl and liquid fuel combustors [11]. Most of these chemiluminescence measurements used traditional lenses to collect the global emissions, and there is insufficient spatial resolution to measure the local equivalence ratio at the flame front. To overcome this deficiency, a Cassegrain optics with high spatial resolution must be used [9, 10, 12]. In the present study, two Cassegrain mirror systems originally designed for Raman scattering measurements [13] are used to simultaneously detect C_2^* and OH^*/CH^* in laminar methane/air flames for calibration purposes. The calibration curve, which is the dependence of OH^*/CH^* and C_2^*/OH^* ratio on the equivalence ratio, is then applied for local equivalence ratio measurements in partially premixed swirling flame.

Experimental Apparatus

The schematic diagram of the Cassegrain optics is shown in Fig. 1. Cassegrain optics consists of a primary and a secondary mirror, which avoids the generation of chromatic aberrations for different wavelengths. The Cassegrain optics is designed by the ray-tracing method. The designed rms spot size of Cassegrain optics is $328\text{ }\mu\text{m}$ and the magnification ratio is 2.36. The experimental setup is shown in Fig. 2. A Hencken burner is used to produce laminar methane/air flames for the calibration measurements. Chemiluminescence signals emanating from the sample volume are collected and focused by a Cassegrainian optics and relayed to the entrance slit of a 0.275 m, f/3.8 spectrometer (Acton Research Co., SpectraPro-275) with a 1200 grooves/mm grating (3 nm/mm dispersion) and a

0.5 m, f/4 spectrometer (SPEX-500M) with a 1800 grooves/mm grating (1.1 nm/mm dispersion). An intensified CCD camera (Princeton Instruments, 576 x 384 array, 22 x 22 μm pixels) is aligned at the exit plane of the spectrometer for monitoring the emission signals. The measured signals are digitized with a 14-bit A/D card connected to a personal computer for data reduction. The spectral coverage of the 0.275 m spectrometer is 36 nm and that of the 0.5 m spectrometer is 14 nm. The entrance slit of spectrometer is set perpendicular to the flame axial direction. Both spectrometers are aligned by a laser beam to ensure that a same length of 3.34 mm is imaged onto each ICCD camera. This enables the image to be divided into points in the spatial direction to obtain the spatial resolution of measurements. The swirl burner is shown schematically in [4]. A non-swirling axial fuel injector with a swirling co-flowing air stream at $S = 1.0$ is employed for the present study. The flowrate of fuel and swirling air is respectively kept constant at 8.96×10^{-5} kg/s and 2.41×10^{-3} kg/s for each of the flames while premixed air is added to the fuel stream to manipulate the fuel and swirl-air momentum flux ratio and to change the fuel tube equivalence ratio. The degree of partial premixing in the central fuel tube is indicated by equivalence ratio, Φ_F , of the tube. The inlet temperature of fuel and air is 294 K. The flames are stabilized by the swirling effect. No pilot fuel injection is used.

Results and Discussion

In order to study the natural chemiluminescence emission a series of flame emission spectra are taken under several different equivalence ratios. Only the $\text{C}_2^*(0, 0)$ vibrational band is shown in the paper. The vibrational bands of $\text{C}_2^*(1, 1)$ and $\text{C}_2^*(0, 0)$ located at near 513 and 516.5 nm are measured using a 0.5 m spectrometer with 300 μm entrance slit width (as shown in Fig. 3) for $\Phi = 0.9, 1.1$, and 1.4 flames. Although Fig. 3 shows significant background light contributions to $\text{C}_2^*(1, 1)$ and $\text{C}_2^*(0, 0)$ bands, their emission intensities are higher than those of $\text{C}_2^*(1, 0)$ band [9]. Therefore, the $\text{C}_2^*(0, 0)$ and $\text{C}_2^*(1, 1)$ bands are used for simulated single-pulse measurements. Under the conditions studied, the profiles of OH^* , CH^* , and C_2^* spectra do not vary much with changes of equivalence ratio. However, the peak intensity of each band spectrum is strongly related to the equivalence ratio. Thus, only the peak intensity of each band spectrum will be used in further studies.

Calibration experiments are performed with the flat-flame burner operated over an equivalence ratio range of 0.8-1.4. For each flame condition, the C_2^* (513 and 516.5 nm) and OH^* (310 nm) band emission spectrum is simultaneously measured using the 0.5 m and 0.275 m spectrometer, respectively. Then the 0.275 m spectrometer is tuned to 430 nm and kept the 0.5 m spectrometer at the same wavelength for repeated CH^* and C_2^* measurements. A simulated 200 pulses is recorded for each equivalence ratio. The spectrum is corrected for background radiation at single-pulse basis. Since the chemiluminescence measurement system collects a length of 3.34 mm of light onto the ICCD camera, the image can be divided into 8 points in the spatial direction to obtain a corresponding spatial resolution of 0.42 mm in the measurements. The dependence of OH^*/CH^* and C_2^*/OH^* ratio on the equivalence ratio is respectively shown in Figs. 4 and 5 for 0.42 mm resolution. The intensity ratios are from background corrected, time-averaged peak intensities. In the present study, the calibration is made for each point, i.e., 8 points have 8 calibration curves.

In order to test the ability of the chemiluminescence measurement technique, we apply the calibration curves obtained from laminar flame measurements to a partially premixed swirling flame ($\Phi_F = 3.1$). The measured radial distribution of equivalence ratio at $X = 20, 40, 60$, and 80 mm is shown in Fig. 6. Experimental results indicate that the measured equivalence ratios at the fuel-side region ($r \leq 2$ mm) are less than those measured at the reaction zone ($2 \text{ mm} < r < 4 \text{ mm}$) for $X = 20$ and 40 mm. This unrealistic result is due to less OH and C_2 are produced in the fuel-side region of the flame. For further downstream locations ($X = 60$ and 80 mm), more OH and C_2 are formed in the fuel-side region and result in the measured equivalence ratio of 1.2-1.3.

Conclusions

Spatially resolved measurements of flame emission spectra using two Cassegrain mirrors and two spectrometers are performed and used to obtain the correlation of the intensity ratio of OH^*/CH^* and C_2^*/OH^* to the equivalence ratio in laminar flames over an equivalence ratio range of 0.8-1.4. The calibration curves are then applied to measure the local equivalence ratio in a partially premixed swirling flame. Experimental results indicate that this non-laser based chemiluminescence technique can only be applied to determine the local flame stoichiometry in the reaction zone of partially premixed swirling methane flames.

Acknowledgment

This research was supported by the National Science Council of the Republic of China under Grant numbers NSC 89-TPC-7-216-003.

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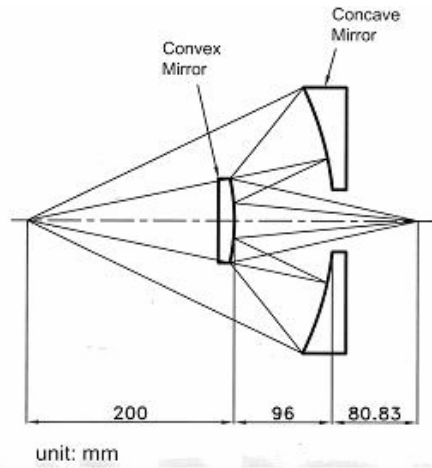


Fig. 1. Schematic diagram of the Cassegrain optics.

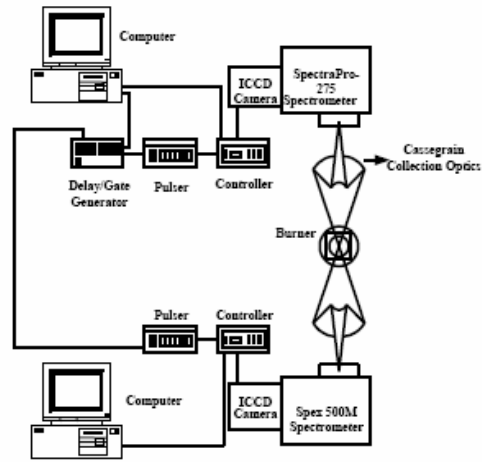


Fig. 2. Experimental setup of measurement system.

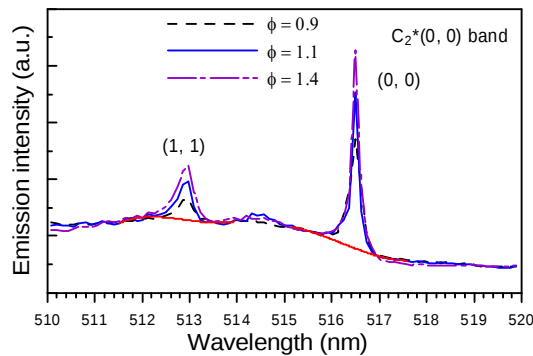


Fig. 3. Flame emission spectra of $C_2^*(0, 0)$ band obtained from three different equivalence ratio.

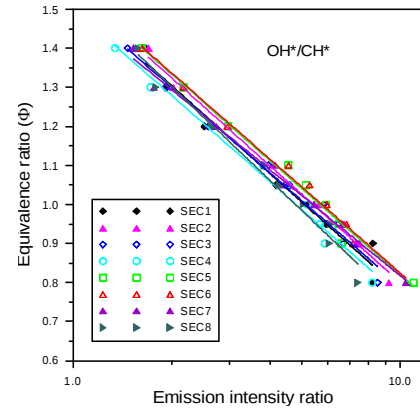


Fig. 4. Correlation of the OH^*/CH^* intensity ratio to the equivalence ratio.

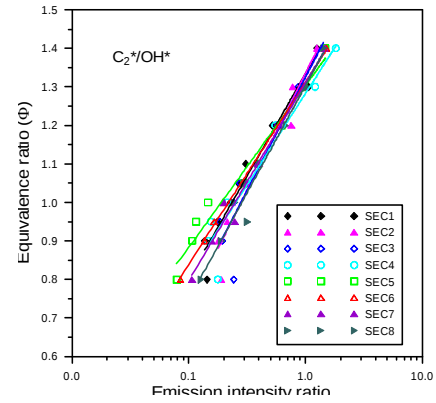


Fig. 5. Correlation of the C_2^*/OH^* intensity ratio to the equivalence ratio.

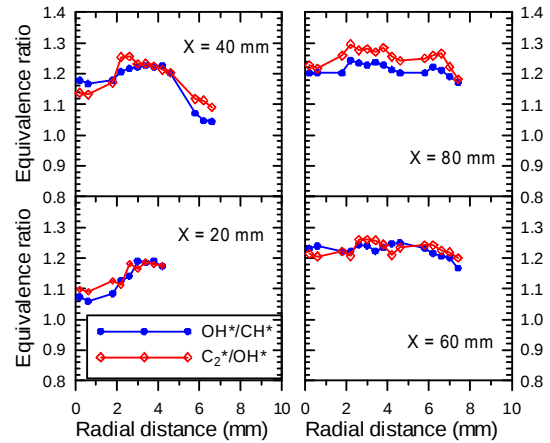


Fig. 6. Time-averaged local equivalence ratio measurements in a partially premixed swirling flame ($\Phi_F = 3.1$).