

Detailed Spectroscopic Measurements of Chemiluminescence from Turbulent Premixed Flames in a Dump Combustor

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ABSTRACT

This paper presents results of experimental study of flame chemiluminescence from turbulent premixed flames in a dump combustor. A detailed spectroscopic measurement of chemiluminescence over the wavelength of 405-495 nm is made for various flow conditions. No effect of turbulence on the relationship between chemiluminescence and heat release is found, suggesting the overall chemiluminescence intensity collected be used as a measure of overall heat release for non-oscillating stable flame. The background-CO₂* subtracted CH* chemiluminescence is found to be more sensitive to the equivalence ratio and premixedness of fuel-air mixture than CO₂* chemiluminescence.

Key Words: Combustion dynamics, Heat release measurement, Chemiluminescence, Turbulent premixed flame

Nomenclature

E_λ	Spectral irradiance	U_m	Velocity in mixing section
T	Tungsten filament temperature	U_c	Velocity in combustor
T_a	Color temperature	ε_λ	Emissivity of tungsten filament
T_i	Inlet mixture temperature	ϕ	Equivalence ratio
		λ	Wavelength

1. INTRODUCTION

Lean premixed (LPM) combustion is widely regarded as the most promising strategy for meeting current and future NO_x emission regulations for industrial gas turbines. Unfortunately, LPM combustion systems are known to be very susceptible to thermo-acoustic instability which is the result of

closed-loop coupling between pressure fluctuation and heat release oscillation. Therefore, the measurement of heat release rate is of great importance in the study of these instabilities. For its relative simplicity, the chemiluminescence emission has been used as an indicator of heat release in such flames and extensively used in combustion instability studies [1-5].

Chemiluminescence is the emission of photons which occur when electronically excited molecules, formed by chemical reactions, return to their ground state. Alternatively, these excited molecules may return to their ground

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state through collisions with walls or other molecules, a significantly faster process than the reactions producing them. Consequently, chemiluminescence measurements of these species will be in direct proportion to their production rates, and can offer a better measure of burning rate than a non-rate based measure. Figure 1 shows a typical spectrum of chemiluminescence emission from a turbulent lean premixed flame at an atmospheric pressure. The strong chemiluminescence emissions in lean hydrocarbon flames are primarily from CH^* , OH^* and CO_2^* (the asterisk indicates an excited species). In these flames, the chemiluminescence emission from CH^* (431 nm) and OH^* (309 nm) occurs at distinctly different and relatively narrow wavelength intervals, while the CO_2^* chemiluminescence lies over a broad wavelength interval (300-600 nm) and overlaps the CH^* and OH^* chemiluminescence spectra. It can be noted that the CO_2^* chemiluminescence can contribute significantly to the measurement of either CH^* and OH^* chemiluminescence if a filter with a broad bandwidth is used to collect either one of these species.

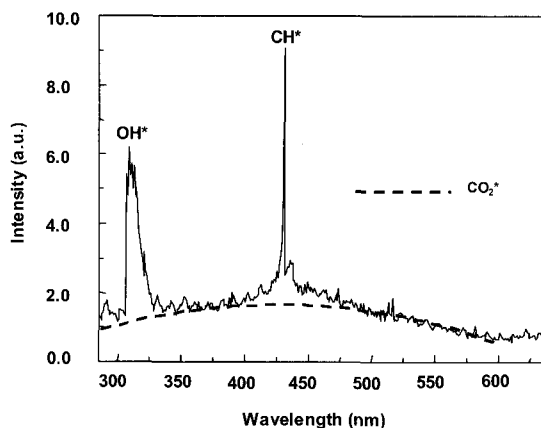


Fig.1. Typical chemiluminescence emission spectrum from the lean premixed dump combustor operating at 100 kPa on natural gas at an equivalence ratio of 0.8 with an inlet temperature of 673K [5].

The base for using chemiluminescence as an

indicator of the location of reaction zone and to infer local and overall heat release rates relies on early experimental studies by Clark [6] and Hurle et al. [7] of jet premixed laminar and weakly turbulent (up to $\text{Re} = 8000 - 10000$) hydrocarbon-air flames near stoichiometric conditions. In these studies it was found that for a fixed equivalence ratio the chemiluminescence captured from the whole flame, hereafter referred to as the overall chemiluminescence, increases linearly with the fuel flow rate, being the slope function of the equivalence ratio.

The relationship between the overall chemiluminescence emission and flow parameters becomes more complicated if the flow is turbulent. The effect of turbulence on chemiluminescence is not clearly known and there exists some uncertainty of whether chemiluminescence will be an adequate measure of heat release in highly turbulent flames where the chemistry of the flame can be changed by the high turbulence. For example, Clark[6] finds that turbulence ($\text{Re}=8000-14000$) reduces the intensity of the overall chemiluminescence in rich and lean propane-air and ethane-air flames. The numerical studies of strained laminar flames by Samaniego et al. [8] and Najm et al. [9] show that the use of CO_2^* as a quantitative measure of heat release is adequate only for well-controlled situations such as two-dimensional and axisymmetric flow conditions, where unsteady strain-rate is the only significant parameter. They suggest that CO_2^* be used with caution as a qualitative measure of heat release in turbulent premixed flames, unless the effects of curvature and three-dimensionality on CO_2^* are further studied. From their experimental results, Najm et al. [9] conclude that "images of CH^* , CH , OH^* and C_2^* are not generally reliable measures of turbulent flame front topology, much less of burning and heat release rates". However, the study by Higgins et al. [10-11] using a counter-flow high-pressure laminar premixed methane-air flame at lean conditions finds no significant dependence of CH^* on the relatively small strain rate (200-700 s^{-1}). However, they suggest that for highly turbulent flows it is expected that flame curvature will

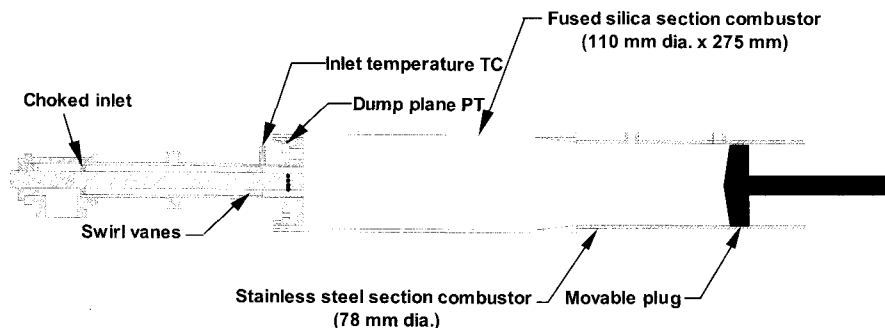


Fig. 2 Schematic drawing of the coaxial dump combustor

affect CH^* .

Nonetheless, chemiluminescence imaging has been used extensively in many studies of turbulent flames as a measure of heat release and/or equivalence ratio as well as a visualization method of flame structure. Most experimental studies have used narrow bandpass filters (typically with the full width at half maximum of 10 nm) to measure the chemiluminescence from CH^* and OH^* . However, as pointed out previously, if the background chemiluminescence from CO_2^* is not properly accounted for, the effect of flow parameters on chemiluminescence and hence the relationship between chemiluminescence intensity and heat release and/or equivalence ratio may not be correctly addressed.

The objective of the present work is to experimentally study the effect of flow parameters such as combustor velocity, equivalence ratio and fuel-air premixing on CH^* and CO_2^* overall chemiluminescence from a swirl-stabilized turbulent lean premixed combustor. A detailed spectroscopic measurement of chemiluminescence over the wavelength of 400-490 nm is made for each flow condition.

2. Experimental apparatus and procedure

2.1 Coaxial dump combustor

The coaxial dump combustor used in this study is depicted in Fig. 2. It consists of an annular mixing section and combustor section.

The combustor consists of an optically accessible fused-silica section followed by

Table 1. Operating conditions

U_m (m/s)	48, 72, 96, 120
U_c (m/s)	4, 6, 8, 10
T_i ($^{\circ}\text{C}$)	200
Equivalence ratios	0.60, 0.75
Reynolds number	$2.05 \times 10^4 - 5.13 \times 10^4$

stainless-steel section. The overall combustor length is adjustable between 0.5 m and 1.35 m by moving a plug in the exit of stainless-steel section. The flame is stabilized on a bluff centerbody which is centered in the annular mixing section using swirl vanes mounted at an angle of 30° with respect to the flow direction. A choke plate at the entrance of the mixing section ensures that the inlet flow is choked at all operating conditions listed in Table 1 and the combustion exit is partially restricted. Natural gas (96 % methane) is used as a fuel and injected well upstream of combustor, providing a well premixed mixture at the inlet of combustor. Air is heated by a 30-kW electric heater. The combustor inlet temperature is monitored by a K-type thermocouple located 40 mm upstream of the dump plane and regulated by a temperature controller. The air and fuel flow rates are measured with linear mass flowmeters.

The apparatus is provisioned with two different fuel injection locations. In one of the locations, the fuel is injected radially outward from the centerbody into the mixing section through 16 equally spaced holes (0.635 mm diameter) located 25.4 mm upstream of the dump plane, providing a partially-premixed fuel-air mixture at the inlet to the combustor. The other injection location is located

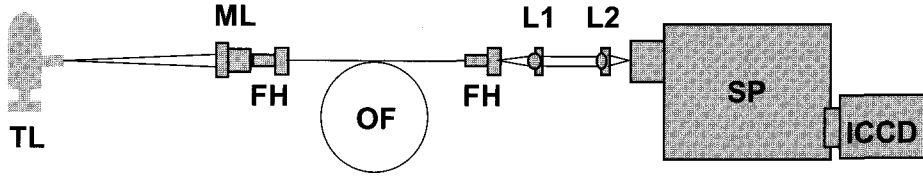


Fig. 3 Schematic drawing of the setup for spectroscopic measurement (TL: Tungsten lamp, ML: Microscope objective lens, FH: Fiber holder, OF: Optical fiber, L1 & L2: Lenses, SP: Spectrometer, ICCD: Intensified CCD camera)

well upstream of the choked inlet to the mixing section, producing a well mixed fuel-air mixture in the combustor.

2.2 Detection system calibration - system efficiency

Collected light, $I(\lambda)$, is converted into a voltage output in the detector through the detection system efficiency, $S(\lambda)$ which depends on the collection efficiency of optics train, including optical fiber, lenses and spectrometer as well as the sensitivity of each camera pixels to the wavelength of light, i.e.,

$$V_{out} = \int I(\lambda) \cdot S(\lambda) d\lambda \quad (1)$$

In other words, if the detection system efficiency does not depend on wavelength, the intensity of light collected by the detection system at different wavelengths will be represented by the same relative quantity as the voltage output at each wavelength. However, it is hardly the case.

In order to determine the detection system efficiency, a light source with a known spectral irradiance is required and a tungsten lamp calibrated at 650 nm is used for this purpose. A schematic drawing of the setup for the spectroscopic calibration of detection system is shown in Fig. 3. Light from the whole tungsten filament is collected using a lens (an achromatic microscope objective, N.A.=0.65) and coupled into a fused-silica optical fiber (N.A.=0.22). The light output from the other end of optical fiber is delivered onto an imaging spectrometer (SPEX 1000M: 1-m, f/8, 1200 grooves/mm) and the dispersed light is

detected using an intensified CCD camera. The spectrometer can capture light spectrum over 10 nm per grating orientation.

Calibration table of the lamp provides the relationship between the color temperature and current setting only at the wavelength of 650 nm. Therefore, it requires a conversion process to determine the spectral irradiance at different wavelengths. The spectral irradiance (E_{λ}) from an object at a temperature of T is given by the Planck's law as:

$$E_{\lambda} = \epsilon_{\lambda} \cdot E_{b,\lambda} = \epsilon_{\lambda} \cdot \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} = \frac{C_1}{\lambda^5 (e^{C_2/\lambda T_a} - 1)} \quad (2)$$

where ϵ_{λ} is the emissivity of tungsten filament which is a function of temperature (T) and wavelength (λ) [12], $C_1=3.7418 \times 10^{-16}$ Wm², $C_2=1.4388 \times 10^{-2}$ mK and T_a is the color temperature. Then, the actual temperature of the tungsten filament (T_{fil}) can be calculated as:

$$T_{fil} = \frac{C_2}{\lambda_{650} \cdot \ln [\epsilon_{\lambda_{650}} (e^{C_2/\lambda_{650} T_a} - 1) + 1]} \quad (3)$$

From this, the color temperature at a different wavelength for the same current setting can be calculated using the emissivity data of tungsten at the filament temperature and the wavelength as:

$$T_{a,new} = \frac{C_2}{\lambda_{new} \cdot \ln \left[\frac{1}{\epsilon_{\lambda_{new}}} (e^{C_2/\lambda_{new} T} - 1) + 1 \right]} \quad (4)$$

Figure 4 shows calculated color temperatures per current applied across the tungsten filament of the lamp for wavelengths of 430 and 470

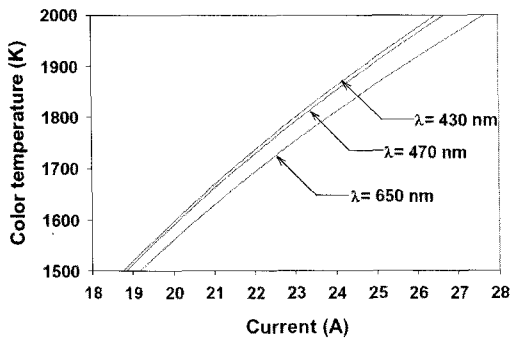


Fig. 4 Color temperature vs. lamp-current settings for different wavelengths

nm as well as for the calibrated wavelength of 650 nm. The wavelength of 430 nm is chosen because it is the center wavelength of a narrow bandpass filter which is commonly used to measure the overall CH^* chemiluminescence. Also, the wavelength of 470 nm is chosen as the center wavelength of a narrow bandpass filter for CO_2^* chemiluminescence measurement. From the relationship between the color temperature and current, the spectral irradiance of tungsten lamp at a given current setting can be calculated using the Planck's law. This is shown in Fig. 5.

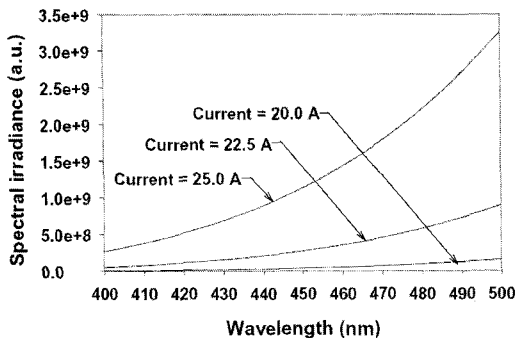


Fig. 5 Calculated spectral irradiance for different lamp-current settings

Table 2 summarizes these results for two lamp-current settings. It shows that the color temperature decreases as the wavelength increases for a given current setting. Also, for a given lamp-current setting the color temperatures at 430 nm or 470 nm are quite different from that calibrated at the wavelength of 650 nm. This suggests that the spectral irradiance curve

Table 2. Color temperature and the ratio of irradiance for the lamp-current settings of 20.0 and 25.0 A

Lamp-current (A)	20.0	25.0
T_{fil} (K)	1655.6	2007.6
$(T_a)@$ 430 nm (K)	1595.5	1919.2
$(T_a)@$ 470 nm (K)	1588.9	1909.5
$(T_a)@$ 650 nm (K)	1560.0	1866.0
$(E_{\lambda=470\text{nm}}/E_{\lambda=430\text{nm}})_1^*$	3.50	2.59
$(E_{\lambda=470\text{nm}}/E_{\lambda=430\text{nm}})_2^{**}$	3.98	2.95

* Based on the relationship between color temperature and lamp-current calculated at each wavelength

** Based on the calibrated relationship between color temperature and lamp-current at 650 nm

determined from the calibration at 650 nm will not correctly represent the actual spectral irradiance from the tungsten lamp. This is illustrated in Table 2 by comparing the ratios of spectral irradiance ($E_{\lambda=470\text{nm}}/E_{\lambda=430\text{nm}}$) at 430 nm and 470 nm: one based on the calibrated relationship between color temperature and lamp-current at 650 nm and that calculated at each wavelength.

2.3 Chemiluminescence spectrum measurement

Chemiluminescence spectrum from the flame is measured using the same setup as the one shown in Fig. 3. Only difference is that the tungsten lamp is replaced with the combustor. Also, the measured chemiluminescence intensity is corrected for the gradual transmittance change of fused silica tube by monitoring chemiluminescence intensity at a fixed reference condition before and after each run.

3. Result and discussion

3.1 Detection system efficiency, $S(\lambda)$

The detection system efficiency is determined from the measured light intensity and the calculated irradiance for a fixed lamp-current setting. A typical system efficiency over the wavelength between 395 nm and 405 nm is shown in Fig. 6. It should be noted that the system efficiency is not constant but changes

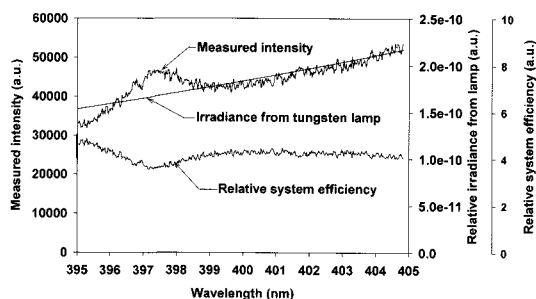


Fig. 6 Detection system efficiency over the wavelength between 395 and 405 nm

with respect to the wavelength of light.

3.2 Chemiluminescence spectrum

Measured chemiluminescence is corrected for the detection system efficiency according to the procedure presented in the previous section. Fig. 7 shows the resulting chemiluminescence spectrum for the premixed flames at $\phi=0.7$ and $T_f=400^\circ\text{C}$. For a fixed equivalence ratio and temperature, the overall chemiluminescence intensity is shown to increase as the mean mixture velocity in combustor and hence mass flow rate of fuel increases. This indicates that the overall chemiluminescence intensity is proportional to the overall heat release from flame. Also, an interesting finding is that the ratio of background- CO_2^* embedded in the chemiluminescence over the wavelength of 420-440 nm to the chemiluminescence over the wavelengths of 460-480 nm is 1.20 for all the velocity cases. This is found not to change for

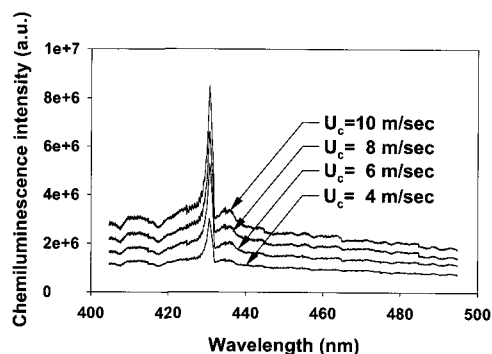


Fig. 7 Chemiluminescence spectrum for well-premixed flames at $\phi=0.70$ and $T_f=400^\circ\text{C}$

all operating conditions run in this study, strongly suggesting that the relative shape of broad CO_2^* -chemiluminescence spectrum does not change with respect to the operating condition. However, as will be seen, the background-subtracted CH^* chemiluminescence is found to be more sensitive to the equivalence ratio and premixedness of fuel-air mixture.

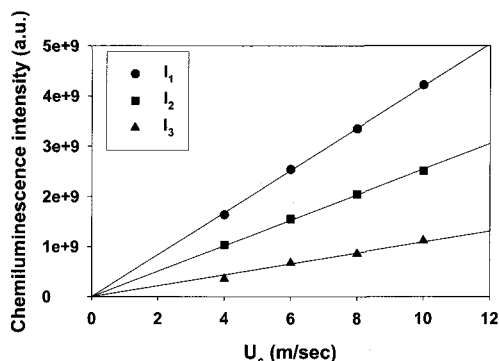


Fig. 8 Chemiluminescence intensity vs. Mean combustor velocity (I_1 :intensity integrated over 420-440 nm, I_2 :intensity integrated over 460-480 nm, I_3 : CO_2^* -subtracted CH^*)

The spectrum is integrated over ranges of wavelength to investigate how the turbulence affects the relationship between the heat release and the chemiluminescence from specific species (CH^* and CO_2^*). The results are shown in Fig. 8 where I_1 and I_2 represent the overall chemiluminescence intensity integrated over the wavelength of 420-440 nm and 460-480 nm, respectively and I_3 represents background- CO_2^* -subtracted CH^* , which is the measure of the chemiluminescence only from CH^* . The background- CO_2^* level is estimated from a curve-fitting of the spectrum over the wavelengths of 405-420 and 440-495 nm where there exists negligible CH^* . It shows that the chemiluminescence from CH^* (I_3) accounts for only about 30% of the chemiluminescence intensity collected over the wavelengths of 420-440 nm (I_1). Also, the overall chemiluminescence increases linearly with respect to the mean mixture velocity in combustor, suggesting there exists no apparent effect of turbulence on the relationship between

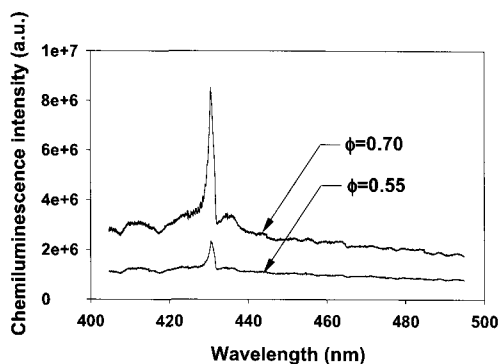


Fig. 9 Chemiluminescence spectrum for well-premixed flames at $U_c=10$ m/sec and $T_i=400^\circ\text{C}$

the overall chemiluminescence intensity and heat release.

The effect of equivalence ratio on the chemiluminescence spectrum for $U_c=10$ m/sec and $T_i=400^\circ\text{C}$ is shown in Fig. 9. For the change of equivalence ratio from 0.55 to 0.70, CO_2^* and background-subtracted CH^* chemiluminescence intensities increase as much as 200% and 470%, respectively.

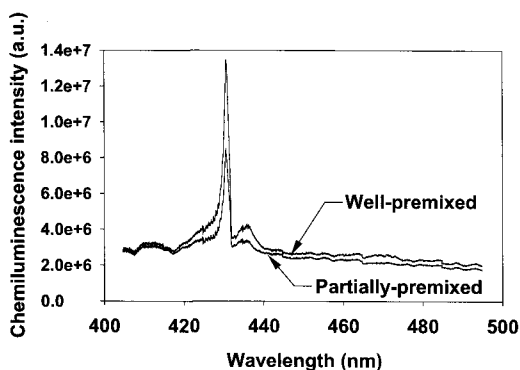


Fig. 10 Chemiluminescence spectrum for well-premixed and partially-premixed flames at $U_c=10$ m/sec, $\phi=0.70$ and $T_i=400^\circ\text{C}$

Figure 10 shows the effect of fuel-air premixing on the chemiluminescence spectrum at $U_c=10$ m/sec and $T_i=400^\circ\text{C}$. The change of fuel-air premixedness results in the change of the shape of chemiluminescence spectrum as well as its magnitude: partially premixed fuel-air mixture results in greater overall chemiluminescence intensity than well-premixed mixture. This is because the partially premixed mixture

results in a locally higher temperature region in the flame. Total chemiluminescence increases about 8% for CO_2^* integrated over 460-480 nm and 67 % for the background- CO_2^* -subtracted CH^* .

4. Summary and conclusion

The effect of flow parameters such as mean mixture velocity, equivalence ratio and fuel-air premixing on CH^* and CO_2^* overall chemiluminescence is studied experimentally for a swirl-stabilized turbulent lean premixed combustor. A detailed spectroscopic measurement of chemiluminescence made for each flow condition over the wavelength of 405-495.

The overall chemiluminescence over the wavelengths of 405-495 nm is found to be a function of mean mixture velocity, equivalence ratio and fuel-air premixing. The overall chemiluminescence increases linearly with respect to the mean mixture velocity in combustor, suggesting there exists no apparent effect of turbulence on the relationship between the overall chemiluminescence intensity and heat release. The change of fuel-air premixedness results in the change of the shape of chemiluminescence spectrum as well as its magnitude. The background- CO_2^* subtracted CH^* chemiluminescence is found to be more sensitive to the equivalence ratio and premixedness of fuel-air mixture than CO_2^* chemiluminescence.

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