Spectral characteristics of a premixed oxy-methane flame in atmospheric conditions

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ABSTRACT

The characteristics of light emission of a premixed oxy-methane flame were experimentally investigated in atmospheric conditions ($T_\infty = 24\ ^\circ$C and $P_\infty = 1.01325$ bar). The objectives of the current study are to investigate the flame luminescence and flame spectra of a premixed oxy-methane flame in a cylindrical tube burner and to derive an empirical formula describing the relationship between chemiluminescence intensity ratio, fuel flow rate, global equivalence ratio, and diluent mole fraction. The mixture velocity at nozzle exit (u_o) was varied in $u_o = (15-35)$ m/s and the global equivalence ratio (ϕ_G) was changed from 0.4 to 2.0 with a cylindrical tube burner of $d_o = 2.03$ mm. A spectrometer and ICCD (intensified charge-coupled device) camera were used to detect flame chemiluminescence with narrow band-pass filters and lenses. The light emission of a laminar premixed oxy-methane flame was more dominant at $\lambda = 308$ nm than at other wavelengths from the measurement of spectral intensity. The intensity of OH* and CH* increased with an increase in mass flow rate of fuel (m_F), adiabatic flame temperature (T_{Ad}), and equivalence ratio (ϕ_G) in $\phi_G = 0.5-1.1$. The intensity ratio of OH*/CH* was expressed as a function of the fuel flow rate, equivalence ratio, and diluent mole fraction (X_D).

1. Introduction

The usage of fossil fuel combustion is the traditional method of power generation by producing heat and light. Meanwhile, the combustion of fossil fuel causes many additional problems, such as pollutant emissions (SOx, NOx) and carbon emissions (CO, CO_2) [1]. Carbon dioxide (CO_2) is known to contribute to the so-called greenhouse effect, fueling fears of global warming [2].

As a new technology to respond global warming, the concept of carbon capture and storage (CCS) has been suggested [3,4]. CCS technology is divided into three methods: pre-combustion, during-combustion, and post-combustion [5]. The method of post-combustion is to capture CO_2 by using filters or absorbents after combustion process. Meanwhile, the method of pre-combustion is to remove the carbon component via gasification or gas reforming before the combustion process.

Oxy-fuel combustion is one of CCS techniques used to solve the problem of greenhouse gas emission. In the process of during-combustion, CO_2 can be directly captured after condensing the products because the result of the chemical reaction between pure oxygen (O_2) and hydrocarbon fuel is CO_2 gas and moisture (H_2O). The method of oxy-fuel combustion is in the limelight due to its easy application in industrial furnaces by retrofitting burners [6–9].

In an oxy-fuel flame, the adiabatic flame temperature is higher than that of a hydrocarbon fuel and air flame because it contains a higher oxygen concentration [10]. An oxy-fuel flame is character-ized by a faster chemical reaction due to its higher flame temper-ature. It is more difficult to control in terms of flame behavior than a hydrocarbon fuel and air flame. Flame luminescence has been used to monitor flame behavior as a diagnostics tool in a lab-scale burners [11], industrial furnace [12], internal combustion engine [13], and gas turbine [14].

Previous researchers reported typical radicals and its charac-teristic wavelength to control and monitor a practical flame with flame spectroscopy [15–18]. The representative chem-iluminescence emitters in a hydrocarbon flame are known to be a hydroxyl radical (OH), a methylidyne radical (CH), a carbon radical (C_2), and a carbon dioxide radical (CO_2) [15,16]. A radical is defined as an intermediate species that is produced during combustion and chemiluminescence is light emission from excited radicals as a
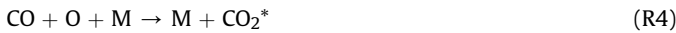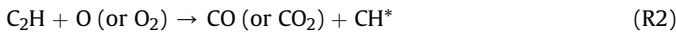

Nomenclature

a.u.	arbitrary unit
CCS	carbon capture and storage
CH*	chemiluminescence from CH radicals
$C_{p,i}$	heat capacity of species i [J/(kg × °C)]
C_2*	chemiluminescence from C_2 radicals
D_i	coefficient of diffusivity of species i (m²/s)
d_o	outlet diameter at nozzle exit (mm)
E_a	overall activation energy of chemical reaction (kJ/mol)
FL	focal length of lens (mm)
Fr_i	Froude number of species i at nozzle exit [$=u_o/(d_o \times g)^{0.5}$]
FWHM	full width at half maximum
f#	f-number of lens aperture
g	acceleration of gravity (m/s²)
ICCD	intensified charge-coupled device
$I_{CH*,2D}$	intensity of Abel-inverted CH* (a.u.)
$I_{CH*,3D}$	intensity of line-of-sight CH* (a.u.)
I_λ	intensity of light emission in wave length, λ (a.u.)
k_i	thermal conductivity of species i [W/(m × °C)]
L	flame length (mm)
Le_i	Lewis number of species i [$=k_i/(\rho_i \times Cp,i \times D_i)$]
M	species of third body
m_F	mass flow rate of fuel at nozzle exit (g/s)
OH*	chemiluminescence from OH radicals
PLIF	planar laser induced fluorescence
P_∞	atmospheric pressure (bar)
R_o	ideal gas constant [J/(mol × K)]
Re_i	Reynolds number of species i at nozzle exit ($=u_o \times d_o/\nu_i$)
r	radial distance (mm)
rms	root mean square
S_L	laminar burning velocity (m/s)
T_{Ad}	adiabatic flame temperature (°C)
T_u	temperature of unburned gas (°C)
T_∞	surrounding temperature (°C)
t_{exp}	exposure time (s)
t_{lip}	thickness of nozzle lip (mm)
u_o	velocity at nozzle exit (m/s)
u'	rms fluctuation velocity (m/s)
V	volt (W/A)
x	axial distance (mm)
X_i	volumetric mole fraction of species i (%)
$\Delta\lambda$	bandwidth of wavelength (nm)
δ	flame thickness (mm)
λ_i	wave length of species i (nm)
ϕ_G	global equivalence ratio
ρ_i	density of species i (kg/m³)
ρ_u	density of unburned gas (kg/m³)
ν_i	kinematic viscosity of species i (m²/s)

result of spontaneous flame radiation due to thermal excitation and chemical reactions [17,18].

The chemiluminescence from each emitter has a characteristic wavelength: (282.9 and 308.9) nm for OH*, (387.1 and 431.4) nm for CH*, and (513 and 516.5) nm for C_2*. In the case of CO_2*, it has a continuous spectrum in the form of background emission in the range of (350−600) nm. The formation routes of OH*, CH*, C_2*, and CO_2* in hydrocarbon flames is known to be the following [15,18,19]:

$$CH + O_2 \rightarrow CO + OH^* \tag{R1}$$

$$C_2H + O \text{ (or } O_2) \rightarrow CO \text{ (or } CO_2) + CH^* \tag{R2}$$

$$CH_2 + C \rightarrow H_2 + C_2^* \tag{R3}$$

$$CO + O + M \rightarrow M + CO_2^* \tag{R4}$$

In a hydrocarbon-air flame, the intensity of light emission from excited radicals can be expressed as a function of fuel flow rate [18], equivalence ratio [11,16], and pressure [20−22]. The emission intensity from excited radical (I_λ) was related to the transition energy in rotational quantum level (E_R) and surrounding temperature (T_∞) [i.e., $I_\lambda = C \times \exp(-E_R/T_\infty)$, where C is the empirical constant] [23,24]. Previous studies in the field of chemiluminescence parameter was summarized in Table 1 [11,16,20,21,23−30].

Several researchers have studied the intensity ratio of chemiluminescence in a hydrocarbon-air flame to extend the applicable range of the flame luminescence results. From a local point of view, Kojima et al. investigated numerically and experimentally the spatially resolved measurement of a laminar premixed methane-air flame from $\phi_G = 0.9−1.5$ with Cassegrain optics in atmospheric conditions [16]. They suggested that OH*/CH* can be used to estimate local flame stoichiometry near a stoichiometric condition.

In the current study, the characteristics of flame spectra of a premixed oxy-methane flame were experimentally investigated in atmospheric conditions ($T_\infty = 24$ °C and $P_\infty = 1.01325$ bar). The flame structure was analyzed with an ICCD camera and the flame spectra were detected with a spectrometer. The objectives of the current study are to investigate the flame luminescence and flame spectra of a premixed oxy-methane flame on a cylindrical tube burner and to derive an empirical formula explaining the relationship between chemiluminescence intensity ratio, fuel flow rate, global equivalence ratio, and diluent mole fraction.

2. Experimental methods

The experimental setup was composed of a cylindrical tube burner, fuel and oxidant delivery lines, mass flow controllers (MFC), the flame luminescence detecting system, and the data acquisition system (DAQ) to study the spectral characteristics of a premixed oxy-methane flame. The schematic of the experimental facility is illustrated in Fig. 1 (a).

An oxy-methane mixture was combusted in a cylindrical tube burner. The cross section of the cylindrical burner was shown in Fig. 1 (b). The outlet diameter of the nozzle exit (d_o) was $d_o = 2.03$ mm and the thickness of the nozzle lip (t_{lip}) was $t_{lip} = 1.0$ mm. The purity of 99.95% oxygen (O_2) and 99.99% methane (CH_4) were used to make the pre-mixture as reactants, while 99.95% nitrogen (N_2) and 99.99% carbon dioxide (CO_2) were used as diluents. A filter of 200 μm mesh was used to prevent flash back, which was equipped between the cylindrical tube burner and gas delivery lines. The mass flow rate for the fuel and oxidant was controlled with two mass flow meters (10 L/min for methane and 20 L/min for oxygen; 5850E, Brooks Instrument Co., Hatfield, PA, USA). These had a linearity of over 99.7% in the range of (1−10) L/min for methane and (2−20) L/min for oxygen. Each of the mass flow meters was calibrated with a dry gas test meter (33 L/min; DCDa-2C, Sinagawa Co., Tokyo, Japan) to ensure the reproducibility