Research Paper

Oxygen temperature variation of a non-premixed oxy-methane flame in a lab-scale slot burner

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HIGHLIGHTS

- Temperature variation effects on oxy-fuel flame length were investigated.
- Flammable area became broadened with increasing oxygen temperature.
- The flame length decreased with an increase in oxygen temperature.
- The concept of effective diameter was used to derive an empirical formula.

ABSTRACT

The effect of temperature variation on the behavior of a non-premixed oxy-methane flame was investigated with a lab-scale slot burner at atmospheric pressure (P_∞ = 1.01325 bar). The characteristics of flame behavior were simulated to analyze the flame structure and were observed by measuring the chemiluminescence from OH and CH radicals with a spectrometer and an intensified charge-coupled device (ICCD) camera. Flammable area was estimated by varying the flow velocity from m_F = 0.02–0.16 g/s (i.e., u_F = 7–50 m/s) for methane gas and m_{Ox} = 0.24–2.71 g/s (i.e., u_{Ox} = 18–117 m/s) for oxygen gas. The oxygen temperature at the nozzle exit (T_{Ox}) was changed from T_{Ox} = 300 to 700 K. Experimental measurements showed that the flammable area broadened as the oxygen temperature increased. The increase in oxygen temperature was associated with a decrease in the flame length. The concept of effective diameter was used to derive an empirical formula for flame length for use in a combustor design.

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1. Introduction

Global warming, caused by greenhouse gases, has become a worldwide concern in recent years [1]. Many efforts have been made to reduce the dependency on fossil fuels in order to reduce the generation of carbon dioxide (CO_2) gases. The exhaust issues from these natural resources have therefore changed the traditional view of fossil fuels as qualified and stable power sources [2]. The concept of carbon capture and storage (CCS) is now accepted as a strategy for overcoming the serious crisis caused by the generation of greenhouse gases.

The techniques of CCS can be divided into three components: pre-combustion, during-combustion, and post-combustion. Methods that involve pre-combustion remove carbon components by gas-reforming or gasification prior to combustion. Post-combustion methods capture CO_2 gas using filters or absorbents after combustion. The during-combustion methods use pure oxygen as the oxidant, rather than air. The products of this oxy-fuel combustion are simply CO_2 gas and moisture at stoichiometric conditions; therefore, CO_2 gas can be easily captured after condensing the exhaust gases [3].

The concept of oxy-fuel combustion has been applied in previous investigations in lab-scale burners [4–6], metal reheating furnaces [7], gas turbine combustors [8], electric arc furnaces [9], and power plants [10].

In general, higher adiabatic flame temperature, greater radiation intensity, and shorter ignition delay time are achieved with oxy-fuel flames than with air as an oxidizer [11,12]. This characteristic means that CO_2 gas or steam can be added to oxy-fuel flows in air-using power plants to reduce the flame temperature and to avoid the durability problems encountered with combustors and heat exchangers. Riaza et al. [13], in experimental study on the

Nomenclature

A^0	Avogadro's number (1/mol)
a	mean buoyancy acceleration [$=0.6 \times g \times (T_f/T_\infty) - 1$)]
a.u.	arbitrary units
CCS	carbon capture and storage
CH^*	chemiluminescence from methylidyne radicals (CH)
DSLR	digital single lens reflex
d_F	width of a fuel jet nozzle exit (mm)
$d_{F,eff}$	effective fuel jet nozzle width (mm)
$d_{F,eff,TOx}$	effective fuel jet nozzle width with consideration for oxygen temperature variation (mm)
d_{Ox}	width of an oxygen nozzle exit (mm)
DO	discrete ordinate model
E_a	global activation energy (kJ/mol)
EDC	eddy-dissipation concept
EDM	eddy-dissipation model
$EINO_x$	emission index of nitrogen oxides (g/kg)
EVM	eddy viscosity model
DRM-19	reduced mechanism based on GRI-Mech 1.2 [35]
FL	focal length of a lens (mm)
FR–EDM	finite rate–eddy dissipation model
Fr_F	Froude number of fuel jet [$=u_F^2/(d_F \times g)$]
Fr_f	flame Froude number [$=(1.5 \times u_F \times Y_{F,st})^2/(a \times L)$]
FWHM	full width at half maximum
$f\#$	f-number of a lens aperture
GRI	gas research institute
g	acceleration due to gravity (m/s^2)
ICCD	intensified charge-coupled device
inverf	inverse error function [i.e., $y = $ erf(x) menas $x = $ inverf(y)] [19]
k_B	Boltzmann constant (J/K)
L	flame length (mm)
l	slot length (mm)
lpm	liters per minute (l/min)
M	third-body collision partner
MFC	mass flow controller
MW_i	molecular weight of species i
m_{AB}	reduced mass of the molecules of A and B [$=m_A \times m_B/(m_A + m_B)$]
m_i	mass flow rate of species i (g/s)
NTP	normal temperature and pressure (20 °C and 1.01325 bar)
OEC	oxygen-enriched combustion
OH^*	chemiluminescence from hydroxide radicals (OH)
P_∞	surrounding pressure (bar)
Q_i	volumetric flow rate of species i (=m^3)
R	universal gas constant [J/(K $\times$ mol)]
Re_F	Reynolds number of fuel jet (=$uF \times dF/vF$)
RSM	Reynolds stress model
RKE	realizable k–ε model
r	transverse distance (mm)
SKE	standard k–ε model
S_e	edge flame propagation velocity (m/s)
S_L	laminar burning velocity (m/s)
T	system temperature (K)
T_{Ad}	adiabatic flame temperature (K)
T_f	mean flame temperature (K)
T_F	fuel temperature at a fuel jet nozzle exit (K)
T_{Ox}	oxygen temperature at an oxygen nozzle exit (K)
$T_{Ox,Ref}$	reference temperature of an oxidizer at NTP (K)
T_∞	surrounding temperature (K)
t_{ex}	exposure time of an ICCD camera (μs)
u_F	fuel jet velocity at a nozzle exit (m/s)
u_{Ox}	oxygen velocity at a nozzle exit (m/s)
w	separation distance between fuel jet and oxygen nozzles (mm)
x	streamwise distance (mm)
$Y_{F,st}$	mass fraction of fuel in stoichiometric conditions
ϕ_G	global equivalence ratio
ρ_b	density of burned gas (kg/m^3)
ρ_{eff}	effective gas density (kg/m^3)
ρ_{Ox}	oxygen gas density at a nozzle exit (kg/m^3)
ρ_F	fuel gas density (kg/m^3)
ρ_u	density of unburned gas (kg/m^3)
σ_{AB}	maximum separation distance between the centers of the molecules of A and B (nm)
v_F	kinematic viscosity of fuel jet (m^2/s)
ω	chemical reaction rate [mol/(m $\times$ s)]

effect of CO_2 gas and steam addition on coal ignition and burnout in an entrained flow burner, showed that the coal ignition temperature varied depending on the CO_2 concentration. However, little difference was noted when steam concentrations were manipulated.

Boushaki et al. [14] used a lab-scale furnace for experimental determination of the geometric effects of a non-premixed oxy-natural gas (NG) jet on different combustion dynamics, focusing on: flame length, lift-off height, and flame stabilization. They reported that the flame length and lift-off height were affected by the diameter of the fuel and oxidant nozzles and by the separation distance between nozzles. In addition, inclining the nozzle angle to create impinging jets also changed the flame stabilization and flame behaviors due to pre-mixing effects near the nozzle exits [15]. Experimental examination of the swirl effect of a non-premixed oxy-NG jet on NOx emission (caused by surrounding air entrainment) revealed that swirl flow from fuel and oxygen nozzles broadened the reaction zone and reduced the NOx emission due to increased turbulence intensity near the nozzle exit [16].

Previous research [17] presented a numerical investigation of the basic flame characteristic of an oxy-methane flame in a gas turbine combustor. The flame structure changed with increases in the

oxygen fraction in the oxidizer, while the reaction zone was thinner at $P_\infty = 40$ bar than at $P_\infty = 17$ bar.

Several researchers working in the field of flame length prediction have suggested theoretical and experimental formulas for predicting flame length. In 1948, Hawthorne et al. [18] studied visible flame length and fuel concentration patterns in a non-premixed turbulent jet with various fuels, including H_2, CO, C_2H_2, and C_3H_8. They derived an equation for isothermal mixing by assuming that a chemical reaction occurs when fuel and air mixing takes place. The equation for the flame length of a simple jet (L_s) is the following:

$$\frac{L_s}{d_F} = \frac{5.3}{X_{F,st}} \times \left(\frac{1}{X_{u,st}/X_{b,st}} \times \frac{T_{Ad}}{T_F} \right)^{0.5} \times \left[X_{F,st} + (1 - X_{F,st}) \times \frac{MW_\infty}{MW_F} \right]^{0.5}$$

(1)

where d_F is the fuel jet nozzle diameter. $X_{F,st}$, $X_{u,st}$, and $X_{b,st}$ are the mole fraction of fuel jet, unburned gas, and burned gas, respectively, at a stoichiometric condition. T_{Ad} is the adiabatic flame temperature and T_F is the temperature at the fuel jet nozzle exit. MW_∞ and MW_F are the molecular weights of the surrounding air and fuel, respectively.