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Flame characteristics of a non-premixed oxy-fuel jet in a lab-scale furnace

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ABSTRACT

The effect of varying the fuel and oxidizer composition on flame characteristics in a non-premixed oxy-methane flame was experimentally investigated in a lab-scale furnace with a slot-type burner. The fuel composition was varied in the range of $X_{F,CH4} = 70\sim100\%$, $X_{F,H2} = 0\sim15\%$, $X_{F,CO} = 0\sim10\%$, and $X_{F,CO2} = 0\sim30\%$ while the oxidizer composition was changed in the range of $X_{Ox,O2} = 70\sim100$ and $X_{Ox,CO2} = 0\sim30\%$. Flow velocity at the nozzle exit was fixed at $u_F = 25$ m/s for the fuel jet and $u_{Ox} = 25$ m/s for the oxidizer. The objective of the current study was to investigate the effect of varying the fuel and oxidizer composition on flame stabilization, flame luminescence, flame slope, liftoff height, flame length, and furnace inside temperature in a non-premixed oxy-fuel flame. The addition of H_2 and CO (carbon monoxide) to a fuel jet had the positive effect of broadening the flammable limit. The hydroxide radical chemiluminescence (OH^*) intensity was related to adiabatic temperature. The flame slope was affected by global equivalence ratio and the mass flow rate between the fuel and the oxidizer. The liftoff height decreased with the increase in edge flame velocity while the flame length decreased with the increase in the Péclet number of unburned gas.

1. Introduction

In recent years, climate change has become an issue around the globe because it causes far-reaching natural disaster. The abnormal climate patterns are known to be caused by greenhouse gases, such as CO_2, CH_4, N_2O, and SF6, which arise due to the use of fossil fuels and the destruction of forest prompted by increases in human populations and economic activities. The concept of carbon capture has been introduced as one alternative for reducing the release of CO_2 into the atmosphere. The technology underlying carbon capture consists of pre-combustion, during-combustion, and post-combustion [1]. The pre-combustion method removes carbon elements from hydrocarbon fuel by reformation, pyrolysis, or gasification while the post-combustion method collects CO_2 using filters or absorbents in an exhaust stack. The during-combustion method uses oxy-fuel combustion in order to capture CO_2 from exhaust gases after condensing H_2O because the flue gas of fossil fuel is theoretically composed of CO_2 and H_2O under stoichiometric conditions [2]. The present study was motivated to develop a high efficiency and environmental-friendly oxy-fuel furnace against greenhouse gas policies in Republic of Korea.

Traditionally, OEC (oxygen-enriched combustion) has been used to reduce fuel consumption in steel reheat furnaces, to increase radiation heat transfer in glass-melting processes, to increase furnace efficiency in the petroleum industry, and to allow the use of low-rank fuels in cement industry [3]. The OEC technology has been adapted to retrofit existing burners or furnaces and use for auto-thermal gasification of biomass fuel [4,5]. In a similar manner to OEC technology, oxy-fuel combustion has been used to reduce cold spots and tap-to-tap time, to increase melting efficiency and productivity, to replace electric energy with thermal energy in EAFs (electric arc furnaces) [6] and to increase the specific impulse in rocker combustors [7]. Oxy-fuel combustion has the merit of decreasing the flue gas volume and increasing the energy savings when compared with air-using combustion because nitrogen does not undergo any the chemical reaction. However, efforts are still needed to decrease the cost of oxygen production.

Previous work has reported higher adiabatic flame temperatures [8], burning velocities [8,9], and OH radical (OH^*) emissions [10,11] for oxy-fuel flames than for air-using flames. The higher flame temperature leads to an increase in thermal NO_x emission if air leakage occurs or if the fuel contains nitrogen, as in the case of

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Nomenclature

a.u.	arbitrary unit
CARS	coherent anti-stokes Raman spectroscopy
CH*	chemiluminescence from methylidyne radicals (CH)
COG	coke oven gas
C_2*	chemiluminescence from carbon radicals (C_2)
$c_{P,b}$	heat capacity of burned gas (J/kg/K)
$c_{P,u}$	heat capacity of unburned gas (J/kg/K)
D_i	mass diffusivity of species i (m^2/s)
DSLR	digital single lens reflex
d_F	fuel jet nozzle width at a nozzle exit (mm)
d_{Ox}	oxidizer nozzle width at a nozzle exit (mm)
EAF	electric arc furnace
FID	flame ionization detector
FL	focal length of a lens (mm)
Fr_G	global fire Froude number ($=u_F/(g \times d_F)^{0.5} \times (1/(1+1/\phi_G))^{1.5}$)
$f\#$	f-number of a lens aperture
g	acceleration of gravity (=9.8 m/s^2)
H	liftoff height (mm)
ICCD	intensified charge-coupled device
I_λ	intensity of light emission (a.u.)
L	flame length (mm)
LIF	laser-induced fluorescence
LNG	liquefied natural gas
l	slot depth (mm)
lpm	liter per minute
MFC	mass flow controller
MFM	mass flow meter
MILD	moderate or intense low oxygen dilution
m_F	mass flow rate of a fuel jet at a nozzle exit (kg/s)
m_{Ox}	mass flow rate of an oxidizer at a nozzle exit (kg/s)
NDIR	non-dispersive infrared absorption
NTP	normal temperature and pressure (20 °C and 1 bar)
n	unit normal vector of a reaction surface
n_f	reaction zone
OEC	oxygen-enriched combustion
OH*	chemiluminescence from hydroxide radicals (OH)
Pe_u	Péclet number of unburned gas ($=(\rho_u \times u_x)/(\kappa_u/c_{P,u})$)
P_∞	surrounding pressure (bar)
R^2	coefficient of determination value (or R-squared)
Re_i	Reynolds number of species i ($=u_i \times d_i/\nu_i$)
r	radial distance (mm)
r_n	radial distance normal to a stoichiometric line
S_e	burning velocity at the front surface of an edge flame (m/s)
$S_{L,st}$	non-stretched laminar burning velocity at stoichiometric condition (m/s)
T	flame temperature (K)
T_a	activation temperature (K)
T_{Ad}	adiabatic flame temperature (K)
T_{Avg}	time-averaged temperature in a lab-scale furnace (°C)
$T_{b,st}$	temperature of burned gas at a stoichiometric condition (K)
T_{mean}	time-averaged mean temperature in a lab-scale furnace (°C)
T_u	temperature of unburned gas (K)
T_∞	surrounding temperature (°C or K)
t_{exp}	exposure time (s)
u_F	fuel jet velocity at a nozzle exit (m/s)
u_L	local flow velocity (m/s)
u_{Ox}	oxidizer velocity at a nozzle exit (m/s)
u_r	flow velocity to radial direction (m/s)
u_x	flow velocity to axial direction (m/s)
u_u	flow velocity of unburned gas (m/s)
w	separation distance between fuel jet and oxidizer nozzles (mm)
$X_{F,i}$	volumetric mole fraction of species i in a fuel jet (%)
$X_{Ox,i}$	volumetric mole fraction of species i in an oxidizer (%)
x	axial distance (mm)
Y_i	mass fraction of species i
α_i	thermal diffusivity of species i (m^2/s)
β_i	coupling function for species i ($=T+Y_i$)
κ_b	thermal conductivity of burned gas (J/m/K/s)
κ_u	thermal conductivity of unburned gas (J/m/K/s)
λ	wavelength of light emission (nm)
$\Delta\lambda$	bandwidth of wavelength (nm)
ϕ_G	global equivalence ratio
ϕ_L	local equivalence ratio
$\rho_{b,st}$	density of burned gas at a stoichiometric condition (kg/m^3)
ρ_u	density of unburned gas (kg/m^3)
θ	degree of flame slope to a burner centerline (deg.)
ν_i	kinematic viscosity of species i (m^2/s)
+, −	non-reactive regions separated by a reaction sheet (+for oxidizer side and − for fuel jet side)

many unconventional natural gases: shale gas, coal-bed gas, tight gas, and gas hydrate. The production of OH radicals is known to be related to an increase in the CO (carbon monoxide) mole fraction because CO_2 is involved in chemical reactions through $CO_2+H \rightarrow CO + OH$ in the oxy-fuel flame [12,13]. These characteristics are thought to be one of reasons why the oxy-fuel flame differs from air-using flames. Previous researchers investigated the variation and effect of reactant composition [13–18], reactant preheating [13,15], injection type [16–18], and flue gas recirculation [17] on combustion dynamics [18] and pollutant emission [15] to develop oxygen-enriched or oxy-fuel combustors. Previous studies in the field of non-premixed oxy-fuel (gas phase) combustion are summarized in Table 1 [13–18].

In the current study, a lifted non-premixed flame was used to investigate the characteristics of liftoff height with varying reactant compositions. From a local point of view, flame stabilization is related to local mixing time and chemical reaction time [19] which indicates that the flame base is stabilized at the point where the burning velocity is equal to the local flow velocity [20]. From a global point of view, the burning velocity of a non-premixed lifted flame is influenced by turbulent intensity [21], large eddy flow [22], local stretch [23], or the mixture fraction gradient [24] near the flame base because the lifted flame is regarded as a partially premixed flame [25]. This flame stabilization is strongly related to the operation range of a practical furnace because the flame stabilization depends on the flammable area and extinction limit.

Heat transfer is achieved as a form of radiation and convection in the furnace. The uniformity of temperature distribution is particularly important, in steel reheat furnaces. The technique of MILD (moderate or intense low oxygen dilution) combustion has been developed to increase thermal efficiency and to reduce fuel consumption and pollutant emission, such as NO_x or CO [26]. The combustor for MILD combustion acts as a well stirred reactor due to the characteristics of zero-dimensional homogeneous chemical