



The effect of CO₂ addition on the flame behavior of a non-premixed oxy-methane jet in a lab-scale furnace



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HIGHLIGHTS

- The effect of CO₂ dilution in an oxidizer was studied in a non-premixed oxy-methane flame.
- A lab-scale furnace was used with a slot-type burner.
- The flame stabilization decreased with increased in the CO₂ mole fraction.
- The time-averaged temperature in the lab-scale furnace increased with decreasing CO₂ mole fraction.

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ABSTRACT

The dilution effect of carbon dioxide (CO₂) in an oxidizer was studied experimentally in a non-premixed oxy-methane flame. A lab-scale furnace with a slot-type burner was used as a model of an industrial furnace. The objectives of the current study are to investigate the flame stabilization, to analyze the flame spectra, and to study the flame behavior of non-premixed oxy-methane flames as the CO₂ mole fraction is varied in an oxidizer. The flame stabilization was estimated by changing the flow velocity at the fuel jet nozzle exit (u_F) and the oxygen nozzle exit (u_{Ox}) from $u_F = 7\text{--}50$ m/s for methane (CH₄) and from $u_{Ox} = 10\text{--}120$ m/s for oxygen (O₂), respectively. The experimental results indicate that the flame stabilization of non-premixed oxy-methane flames decreased with increases in the CO₂ mole fraction in the oxidizer. The flame spectra of non-premixed oxy-methane flames had a maximum intensity at the wavelength (λ) of $\lambda = 308$ nm. The reaction zone of non-premixed oxy-methane flames was broadened by the addition of CO₂ to the oxidizer.

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1. Introduction

Climate change, caused by the use of fossil fuels, is itself causing an energy crisis because most power generation comes from the combustion of fossil fuels as an energy source [1]. The concept of carbon capture has been suggested as a strategy for reducing greenhouse gas generation due to fossil fuel combustion. Carbon capture technology consists of three components: pre-combustion, during-combustion (oxy-fuel combustion), and post-combustion [2].

Oxy-fuel combustion allows for the direct capture of carbon dioxide by condensing flue gases without the need for filters or absorbents. This is because flue gases mostly consist of carbon dioxide (CO₂) and water vapor (H₂O). Oxy-fuel combustion is characterized by a faster chemical reaction, higher adiabatic flame temperature, and faster burning velocity when compared to air combustion [3]. Oxy-coal combustion, in contrast to air-fired coal

combustion, is influenced by the molecular diffusion rate of oxygen (O₂), which affects the ignition delay of coal particles [4].

Industrial processes have used oxygen-enriched air to enhance flame temperature and thermal efficiency [5]. Wu et al. studied the effect of oxygen enrichment on the characteristics of natural gas and air flames [6] and reported that an increase in the oxygen mole fraction in air leads to a higher heating rate and a lower fuel consumption due to the reduction of an inert gas (N₂) that is not involved in a combustion process.

In general, the concept of exhaust gas recirculation (EGR) has been used to reduce the emission of nitrogen oxides (NO_x) because the addition of exhaust gases into reactants decreases flame temperature [7]. In a similar way, the concept of flue gas recirculation (FGR) has been studied in an effort to control flame temperature in oxy-coal fired furnaces as a means of CO₂ capture. CO₂ addition into an oxidizer by FGR is now under investigation in industrial regenerative oxy-fuel combustion furnaces in order to achieve energy savings and to control furnace temperature, while achieving complete combustion under conditions of low excess oxygen. CO₂ addition to oxy-fuel flames is known to improve plant

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Nomenclature

a.u.	arbitrary units	T_{∞}	surrounding temperature ($^{\circ}\text{C}$ or K)
CH*	chemiluminescence from methylidyne radicals (CH)	u_F	fuel jet velocity at the nozzle exit (m/s)
d_F	width of the fuel jet nozzle exit (mm)	u_{Ox}	oxygen velocity at a nozzle exit (m/s)
d_{Ox}	width of the oxygen nozzle exit (mm)	w	separation distance between the fuel jet and oxygen nozzles (mm)
Fri	Froude number of species i ($=ui^2/(di \times g)$)	X_{CO_2}	volumetric mole fraction of carbon dioxide gas in an oxidizer (%)
$f\#$	f -number of the lens aperture	λ	wavelength of light emission (nm)
g	acceleration due to gravity (m/s^2)	ϕ_G	global equivalence ratio
H	liftoff height (mm)	$\rho_{b,st}$	density of burned gas at a stoichiometric condition (kg/m^3)
L	flame length (mm)	ρ_u	density of unburned gas (kg/m^3)
l	slot depth (mm)	ρ_i	density of species i (kg/m^3)
lpm	liters per minute (l/min)	ν_i	kinematic viscosity of species i (m^2/s)
OH*	chemiluminescence from hydroxide radicals (OH)		
P_{∞}	surrounding pressure (bar)		
Re_i	Reynolds number of species i ($=ui \times di/\nu_i$)		
T_{mean}	time-averaged mean temperature in a lab-scale furnace ($^{\circ}\text{C}$)		

efficiency due to the lower gas volume and better operational flexibility [8].

Wang et al. studied the effect of hydrogen (H_2) and carbon dioxide (CO_2) on the cellular structure of spherically propagating flames in the laminar premixed methane–air flame [9]. They found that an increase in the H_2 mole fraction of the reactants promoted the cellular structure, while an increase in the CO_2 mole fraction in the reactants reduced the cellular structure due to the variation of intrinsic and hydrodynamic instabilities.

Previous researchers used a turbulent premixed methane–air flame and OH planar laser-induced fluorescence (PLIF) measurements to investigate the effect of carbon dioxide (CO_2) and water (H_2O) on the turbulent burning velocity [7] and the local structure of the flame front [10] at high pressure (0.5 and 1.0 MPa) and high temperature (573 K). CO_2 addition to the reactants resulted in a decrease in thermal diffusivity, local Lewis number, and turbulent burning velocity. Flame structure consisted of small scale wrinkled flame fronts under ambient conditions ($P_{\infty} = 1$ bar and $T_{\infty} = 300$ K), while the addition of CO_2 gas to the reactants led to a decrease in the flame front area and a decrease in the flame front propagation velocity due to the suppression of these small scale wrinkles.

The addition of CO_2 to an oxidizer increased radiation heat transfer due to higher gas emissivity, heat capacity, and soot volume fraction in the flames [11]. The increased radiation heat transfer is useful for the uniform heat treatment of steel materials or ingots during the steel-making process. Oxygen-enriched or oxygen-fuel combustion using CO_2 recirculation is thought to be one of ways of controlling furnace temperature and thereby reducing fuel consumption. However, very few fundamental studies have considered the use of a non-premixed oxy-fuel flame and CO_2 addition to the oxidizer for application to industrial furnaces.

The current study presents an experimental investigation of the effect of CO_2 addition to a non-premixed oxy-methane flame on the flame behavior in a lab-scale furnace, as an exploration of advanced combustion technology with the concept of the oxy-fuel combustion. The objectives are to investigate the flame stabilization, to analyze the flame spectra, and to study the flame behavior of a non-premixed oxy-methane flame when the CO_2 mole fraction is varied in an oxidizer. This research is anticipated to identify fundamental technology for a flue gas recirculated regenerative oxy-fuel combustion system with CO_2 capture for use in industrial heating processes.

2. Experimental methods

The effect of CO_2 dilution of an oxidizer on the flame behavior of a non-premixed oxy-methane jet was investigated by installing the

experimental facility shown in Fig. 1(a). The experimental setup was composed of three devices: a lab-scale furnace, optics for flame luminescence detection, and a temperature-measuring apparatus.

A 10 kW lab-scale furnace was located at the center of the experimental setup. The internal size of this furnace was 250 mm in width (W), 250 mm in depth (D), and 800 mm in height (H). A slot-type burner was installed inside the lab-scale furnace. As shown in Fig. 1(b), the width of the fuel jet nozzle exit (d_F) was $d_F = 0.24$ mm, and the width of the oxidizer nozzle exit (d_{Ox}) was $d_{\text{Ox}} = 0.52$ mm. The separation distance between the two nozzle exits (w) was fixed at $w = 8$ mm, and the depth of the nozzle exits (l) was $l = 20$ mm. Heat loss from furnace walls was prevented by shielding the furnace with an insulator of 48% Al_2O_3 and 52% SiO_2 (FXL D-Block, ITM Co., Ltd., Kozaki, Chiba Prefecture, Japan). Optical assessments were made through two panes of a quartz window glazed on each side of one furnace wall. The size of this quartz window was 110 mm in width, 210 mm in height, and 5 mm in thickness. The surface case of the lab-scale furnace was manufactured with a stainless steel plate (AISI 304).

The lab-scale furnace was connected with fuel and oxidizer delivery lines. Methane (CH_4) and pure oxygen (O_2) were used as the fuel and oxidizer, respectively. Carbon dioxide (CO_2) was used as the diluent gas in the oxidizer. The purities of the fuel, oxidizer, and diluent gas were 99.99% for methane, 99.95% for oxygen, and 99.99% for carbon dioxide. The flow rate of each gas was controlled with a mass flow meter (MFM) (5851E, Brooks Instrument Co., Hatfield, PA, USA), which had a linearity of over 97% in the range of 10–100 lpm. The flow meter was calibrated with a dry gas test meter (DA-16A-T, Sinagawa Co., Tokyo, Japan) before use. The flow rate was regulated by controlling the MFM with Lab-VIEW modules (NI cDAQ 9172, NI 9263, and NI 9205, National Instruments Co., Austin, TX, USA).

Flame luminescence was analyzed with a spectrometer, which was composed of a grating body (Acton SP2150i, Princeton Instruments Inc., Trenton, NJ, USA), signal controller (spectra hub, Princeton Instruments Inc., Trenton, NJ, USA), and photo-diode (PD471, Princeton Instruments Inc., Trenton, NJ, USA). The focal length (FL) was $FL = 500$ mm, and the spectral resolution of the spectrometer was 1 μm in the range of 100–800 nm.

The light emission from the non-premixed oxy-fuel flame was measured with an intensified charge-coupled device (ICCD) camera (iStar DH-334T, Andor Technology PLC Co., Belfast, Northern Ireland, UK) fitted with an F-mount macro lens (Nikkor 105 mm f/4.5 UV, Nikon Co., Tokyo, Japan). The chemiluminescence of OH and CH radicals (OH* and CH*) was collected using a narrow band

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