Experimental and Numerical Study of Oxygen Enrichment on Methane Diffusion Flame in a Triple Port Burner

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Abstract

Oxy-enriched combustion technology is one of cost-effective approaches to improve the flame stability and combustion efficiency. In general, a triple port burner can provide a simple diffusion flame to investigate the oxygen enrichment effect on the flame characteristics. In this study, the flame shape would shift from normal diffusion flame (NDF) to inverse diffusion flame (IDF) accompanying with changing flame color when the oxygen concentration in oxidizer is increasing. The operational range of IDF with various velocity ratios and oxygen enrichments is demonstrated. It appears that length of IDF becomes shorter as oxygen enrichment is increasing. Besides, numerical simulation for two cases (Ω=40% and 60%) is also performed and indicates the significant increase of carbon monoxide concentration in IDF. It is argued that increasing oxygen in IDF would improve the oxidation reaction of soot and lead to abundant carbon monoxide production.

Keywords: oxy-enriched, inverse diffusion flame, triple port burner.

1. Introduction

Owing to reduce fossil fuel consumption and carbon oxide emission, a large number of approaches and strategies are proposed to booster the combustion efficiency of nowadays fuel-firing combustion systems. Among these promising methods, oxy-enriched combustion technology is sophisticated and cost-effective to improve the flame stability and combustion efficiency. Yepes et al. [1] discovered that the laminar burning velocity increases by almost 25% with an increment of 4% oxygen in the oxidant. When oxygen concentration increases to 35%, the yield of abundant O and OH radical would enhance chemical reaction. Leo et al. [2] found out that the thermal excitation is the dominant excitation mechanism of OH* at oxygen contents above 35%. Han et al. [3] studied the velocity of premixed flame methane/O_2/N_2 with various oxygen enrichments in air from 21% to 98.5%. It shown that the flame speed always has a maximum at stoichiometry, and the increase of the oxygen content from 21% to 98.5% increases by 600% the laminar flame speed at stoichiometry. Besides, the oxygen enrichment on the flickering frequency and amplitude of the flame was also studied by Legros et al. [4]. They found that increasing oxygen content induces a shift toward lower flickering frequencies and smaller relative amplitude due to the decrease of the flame length. Besides, some studies [5, 6] examined the soot formation in diffusion flames where the oxidizer was oxygen enriched air; they proved the increase of soot formation with oxygen enrichment.

Regarding to diffusion flames, there are two types, normal diffusion flame (NDF) and inverse diffusion flame (IDF), respectively. The IDF is a special flame with an inner oxidizer jet surrounded by an outer fuel jet. Shaddix et al. [7] showed that the relative positions of OH, PAH, and soot were very similar in the normal and inverse steady flames. Besides, PAH signals and soot concentrations of the IDF are somewhat smaller than those of the NDF. Liu and Smallwood [8] found that the central air jet has a significant effect on the flame structure and sooting characteristics of the flame in a three-port co-annular burner. Johnson and Sobiesiak [9] studied the hysteresis of methane inverse diffusion flame. Their numerical results suggest that when the local equivalence ratio approaches to one in upstream of the flame, the partially premixed flame (PPF) propagates upstream and stabilizes as an IDF.

In this study, the methane/air flame with various oxygen enrichments is experimentally and numerically investigated. The shift of diffusion flame structure from NDF to IDF depending upon increasing oxygen concentration in oxidizer is observed.

2. Methodology

The objective of this work is to theoretically and experimentally investigate the flame behaviors of methane diffusion flames with oxy-enriched oxidizer and N_2O addition by varying the velocity ratio (R=V1/V2). Flame images and chemiluminescence technique are used on a triple port burner. The outer air stream velocity was maintained at 40(cm/s). The central oxygen concentration is expressed as:

$$\Omega = \left(\frac{X_{O_2}}{X_{O_2}+X_{N_2}}\right)\cdot 100\% \qquad (1)$$

The experimental apparatus is shown in Fig. 1. It consists of three concentric tubes where the oxidizer, methane, and air flow out, respectively. The flow rates of three stream were controlled using mass flow controllers (BROOKS 5850E series). To capture the flame shape, a digital camera (Nikon D80) was used. To measure the spectrum intensity from soot radiation, the emission light from the flame was guided to a spectroscope (Ocean Opitics; USB4000-UV-VIS) with an optical fiber (P100-2-UV/VIS).

In numerical simulation, a commercial code, CFD-ACE, is incorporated with detailed gas-phase mechanisms in CHEMKIN format to simulate the methane/air diffusion flame with various oxygen enrichments. Detailed gas-phase is applied and the reaction rate is represented by the modified Arrhenius expression. The GRI-Mech 3.0 mechanism is used for gas phase reactions; it comprises 53 species and 325 reaction steps.

3. Results and Discussion

Figure 2 shows the experimental flame appearances in the condition of fixed velocity ratio and various Ω. Depending increasing the central oxygen concentration Ω, the flame appearance indicates that partial premixing reduces and ultimately eliminates soot particles in methane flames. The NDF appears in very yellow-orange color for Ω=40%. When oxygen concentration increases to Ω=30%, it is interested to note that the blue weak curved flame front, which is a partially premixed flame, moves upstream. When the oxygen concentration continuously increases to Ω=40%, the PPF propagates upstream to ignite the IDF and the soot-free blue flame suddenly becomes a yellow-orange sooty flame. It is speculated that the anchored IDF increases the temperatures along the flame centerline region, which greatly accelerates the pyrolysis of the fuel, leading to enhanced soot formation. However, increasing the central oxygen concentration Ω will shorten the length of IDF, and eventually flame color changes from yellow-orange to silver-yellow. The silver-yellow flame color is probably contributed by the present of carbon monoxide [10]. It speculates that high Ω provides more oxygen in IDF. It results in reducing soot and increasing carbon monoxide in IDF.

In order to map out the operational range of IDF, the inception of IDF formation and extinction with various oxygen-enrich concentrations and fixed velocity ratio R is determined. Figure 3 shows the oxy-enriched limitation of IDF formation and extinction with various velocity ratios. By increasing velocity ratio R, the maximum concentration of oxygen enrichment in oxidizer for IDF formation is firstly decreasing and then increasing. It appears the main mechanism of IDF formation is shifted with increasing velocity ratios. As to IDF extinction, high oxygen-enriched concentration is necessary to stabilize the flame on the burner port as the velocity ratio R is increasing. In the same velocity ratio R, when fuel velocity V_2 is increasing, the oxy-enriched requirement of IDF formation and extinction are correspondingly increasing.

Figure 4 shows the numerical results of CO and C_2H_2 concentration in the flames of Ω =40% and 60% and fixed R = 7. C_2H_2 is precursor of soot, and it can represent the location of soot in the flames. Whe the central oxygen concentration increases from 40% to 60%, the length of C_2H_2 distribution is reducing, analogous to experimental results. Besides, the CO concentration is apparently increasing when Ω increases to 60%. It proves that the increase of oxygen concentration would enhance oxidation reaction of soot and accompany with abundant CO production.

4. Conclusions

In this work, we use the triple port burner to investigate the flame shapes of diffusion flame with various oxygen enrichments. The experimental results show that flame shape changes from partially premixed flame (PPF) to inverse diffusion flame (IDF). The corresponding flame color shifts from yellow-orange to silver-yellow. It assumes that the increasing oxygen in IDF would improve the oxidation reaction of soot and yield abundant carbon monoxide. The numerical results demonstrate that the CO concentration in IDF certainly reduce when the central oxygen concentration increases from Ω=40% to 60%. Besides, the oxy-enriched requirement of IDF formation and extinction are also investigated with various velocity ratio R and fuel velocity V_2.

5. Acknowledgements

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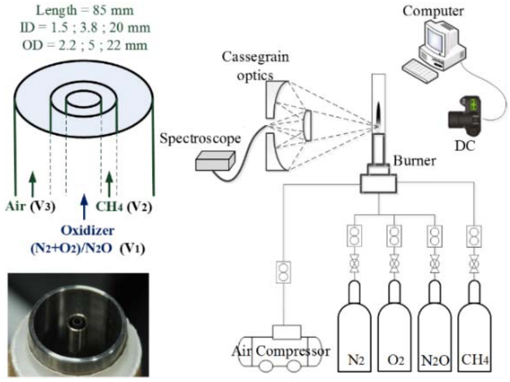

Figure 1. Experimental facility schematics.

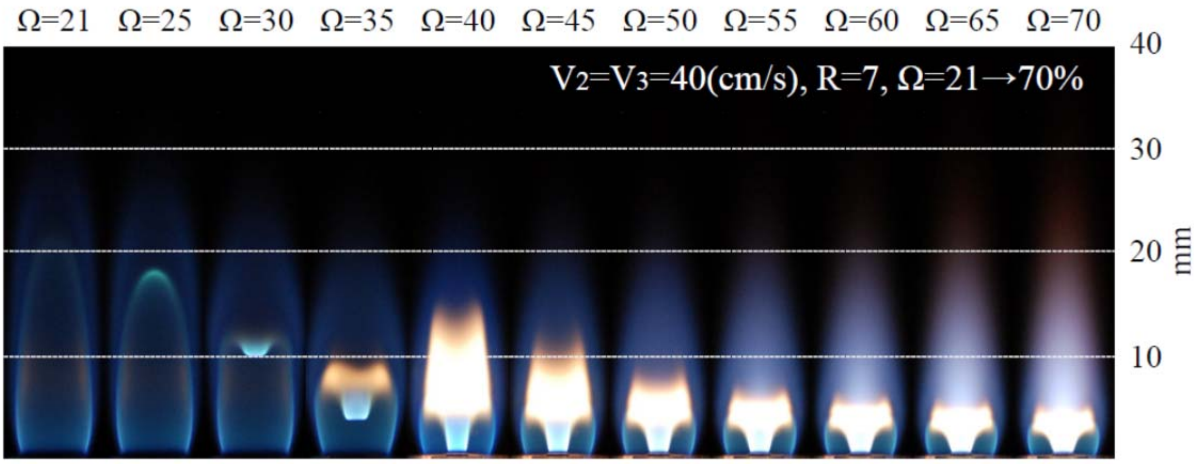

Figure 2. The visible flame appearances for V_2=V_3=40 cm/s and R=7 with increasing Ω.

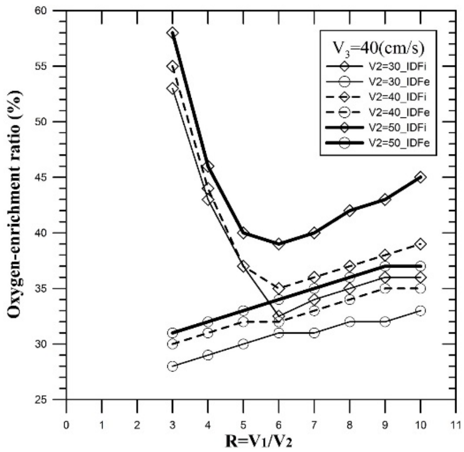

Figure 3. The limitation of IDF formation (labeled in diamonds) and extinction (labeled in circles) in terms of oxygen enrichment ratio and velocity ratio.

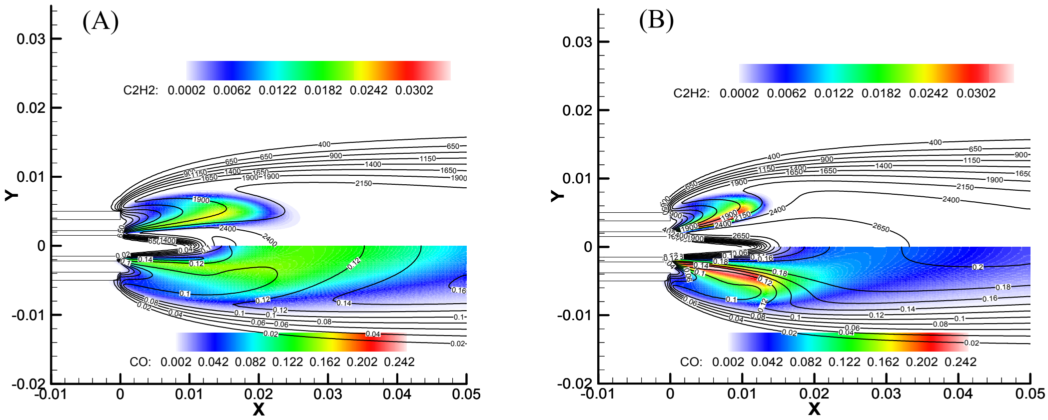

Figure 4. The numerical results of CO and C_2H_2 concentration in the condition of Ω= (A) 40% and (B) 60%.