Effects of Coflow Dilution with Carbon Dioxide on the Methane Diffusion Flame Characteristics

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Abstract

Recirculated carbon dioxide is often used to replace air nitrogen for dilution in oxy-fuel combustion. Experimental and numerical studies are performed to investigate the effects of different ratios of CO_2/O_2 in the coflow on laminar CH_4 diffusion flame characteristics. The various ratios of CO_2/O_2 in the coflow are used to compare with air-coflow (21% O_2 and 79% N_2) condition. Experimental measurements of the temperature and flame chemiluminescence profiles are used to validate numerical simulation results for various CO_2 dilution conditions. The numerical simulation is employed to further investigate the flame and reaction characteristics of the CO_2 diluted oxy-methane combustion. One of the interesting findings is the open flame tip which is difficult to identify from experiment. The O_2 and CO_2 concentrations within the coflow promote most of the reaction rates up to many times higher than the situation of air-coflow. It means that reaction rate is enhanced when oxygen concentration is high but high concentration of CO_2 may significantly promote some forward and reverse reactions involving CO_2, especially the R99 reaction. The liftoff heights are also affected by various diluents. Due to high heat capacity, when CO_2 dilution ratio is more than 70% the liftoff heights will be reduced suddenly by 50%.

Keywords: oxy-fuel, coflow, carbon dioxide, dilution effect, diffusion flame

1 Introduction

The greenhouse gases (GHG) emission on global climate change is strongly related to massive carbon dioxide (CO_2) emission [1]. Accordingly, various strategies to reduce carbon dioxide emissions to the atmosphere are proposed [2] [3], such as carbon dioxide capture and sequestration (CCS), renewable energy sources, catalytic combustion [4], lean combustion [5], and clean biofuels [6]. Among these, oxy-fuel combustion [7] is one of the attractive methods of timely importance to facilitate carbon dioxide capture and sequestration (CCS) for reducing CO_2 emissions. In a conventional air combustion process, CO_2 is considered as a dilute gas in the flue gas, resulting in costly capture using amine absorption with poor efficiency due to the low CO_2 concentration in the flue gas stream full of nitrogen [8]. CO_2 not only can be sequestered into the deep saline aquifers but also used for enhanced oil recovery (EOR) or enhanced coal bed methane recovery (ECBM) [9]. In oxy-fuel combustion, CO_2 is recirculated to mix with pure oxygen for dilution in the combustion to generate high concentration of CO_2 in the flue gas stream to facilitate CCS and to achieve the ultimate goal

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of zero CO_2 emissions. Carbon dioxide has been used to dilute the air stream or completely replace nitrogen in the air. For both cases the flame burning velocity will be affected by the following mechanisms: (1) change of transport and thermal properties of the mixture due to CO_2, (2) direct chemical effect due to reactions involving CO_2, and (3) the enhanced radiation effect by CO_2 [10]. CO_2 is not only an inert gas but also may directly participate in chemical reactions of the flame through R99: CO+OH ⇔CO_2+H and others [11, 12]. Furthermore, CO_2 in this chemical reaction (R99) competes with other reactions for atomic hydrogen, leading to the formation of CO and active radical OH [13]. It also has been shown that the effect of high CO_2 concentrations on combustion rates can be attributed to its participation in the chemical reactions during oxy-fuel combustion of methane [14]. In this paper effects of various ratios of CO_2 dilution in the oxygen stream on the coflowing methane diffusion flame stabilization is studied .

2 Experimental Setup and Simulation

As shown in Fig. 1, the co-flowing methane diffusion burner consists of a central stainless steel circular tube (OD = 1 mm) for methane stream and co-flowing oxygen stream with various dilution ratios of CO_2 confined in a circular quartz chamber (ID = 30mm). The quartz chamber is 300mm in length and with 3 inspection holes (D = 1 mm) at the height of 35mm above jet exit. The co-flowing oxygen and CO_2 diluent are premixed in the pipeline and the contoured settling chamber with honeycomb and meshes. The fuel and coflow are metered by rotameters and electronic flowmeters, and the temperature is measured by a non-catalyst coated R-type thermocouple, as shown schematically in Fig.1. The liftoff heights and flame shapes of the co-flowing diffusion flame are obtained by photographic images by a digital camera (Nikon D80). To numerically simulate the coflow methane diffusion jet flame, the relevant governing equations are solved by using the commercial package ESI-CFD and CHEMKIN with GRI-3.0 mechanism for flow, heat transfer and chemistry/mixing computations. A flame-zone reinforced grid system is used to solve the discretized equations with a control volume formulation in accordance with the SIMPLEC algorithm [15].

3 Results and Discussion

The distribution of temperature (below 2000K) measured at a position of 35mm above jet exit are used to compared with simulation results in Fig. 2. The agreement between the measured and the calculated temperature profiles for various dilution conditions is satisfactory. The slight deviation between the calculation and measured values mainly results from the non-activated radiation simulation model within the simulation program. Figure 3 shows the comparison of the experimental flame chemiluminescence image of the excited species CH* and the numerical simulation results of CH profile. . The agreement is acceptable. It is interesting to find from the numerical results that for high percentage (above 50%) CO_2 dilution the flame tip is open but it is difficult to find in the experiment due to small size of the flame and the quartz confinement. From sensitivity analysis of the methane reactions, reaction steps R3 and R99 are most important. Figure 4 shows reaction rates (Kmol/m^3·sec) of dominant step R3: O+H_2 ⇔ H+OH with coflow at various conditions of (1) air - 21% O_2+79% N_2, (2) 30%O_2+70%CO_2, (3) 40%O_2+60%CO_2, (4) 50%O_2+50%CO_2 and (5) 60%O_2+40%CO_2. The effect of substituting N_2 with CO_2 will induce an open flame-tip feature in cases of (2), (3) and (4). The flame tip closes back in the case (5). Figure 5 shows simulated reaction rates of R99: OH+CO ⇔H+CO_2 with coflow at various conditions of (1) air - 21% O_2+79%, (2) 30%O_2+70%CO_2, (3) 40%O_2+60%CO_2, (4) 50%O_2+50%CO_2 and (5) 60%O_2+40%CO_2. By substituting N_2 with CO_2, it shows that the reverse reaction rate of R99 becomes stronger by 5 times. Besides, the reaction rates of R99 increase in both forward and reverse direction in all conditions. The reverse reaction rate drops in case (5).. Thus, the CO_2 from coflow has less chance to promote the reverse reaction. Figure 6 shows the variation of flame liftoff height with different diluent at various conditions. The measurement results indicate that when the ratio of diluent (CO_2) in coflow increases, the liftoff heights will be increased. But for CO_2, when the dilution ratio increases over 70% the flame liftoff height decreased. It is believed that the CO_2 has greater heat capacity to reduce the flame burning velocity [16] [17] and the flame becomes unstable and lifts off more easily.

4 Conclusion

The present work aims at the effects of CO_2 dilution on the methane jet flame characteristics. The effects of different concentrations ratio of carbon dioxide and oxygen in the coflow is studied experimentally and numerically. The numerical simulation results are validated against experimental measurements of temperature and flame chemiluminescence profiles for various dilution conditions of CO_2 in the coflow. The methane diffusion flame is affected by the different ratios of CO_2/O_2 in the coflow. The open flame tip is observed from simulation results which is difficult to identify from the experimental flame images. Relative busy reactions are found due to a high concentration of O_2 regardless of retarding effects from high concentration of CO_2 in comparison with the case of air in coflow. Not only the chemical effect but also the heat capacity have the obvious influence on methane jet flame. Especially when CO_2 ratio is more than 70% the liftoff heights will be reduced .

5 Figures

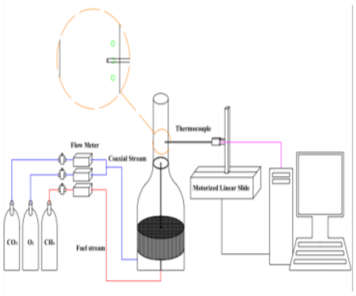

Fig.1 Experimental setup.

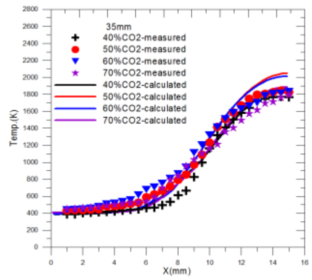

Fig.2 shows that simulation and measured temperatures are compared and have the same tendency.

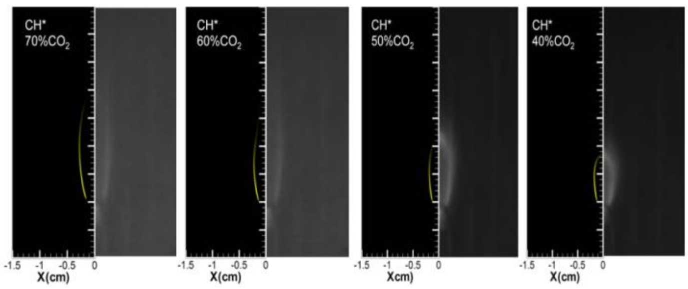

Fig.3 Comparison of the species CH, measured CH* image(right) and computed CH profile(left).

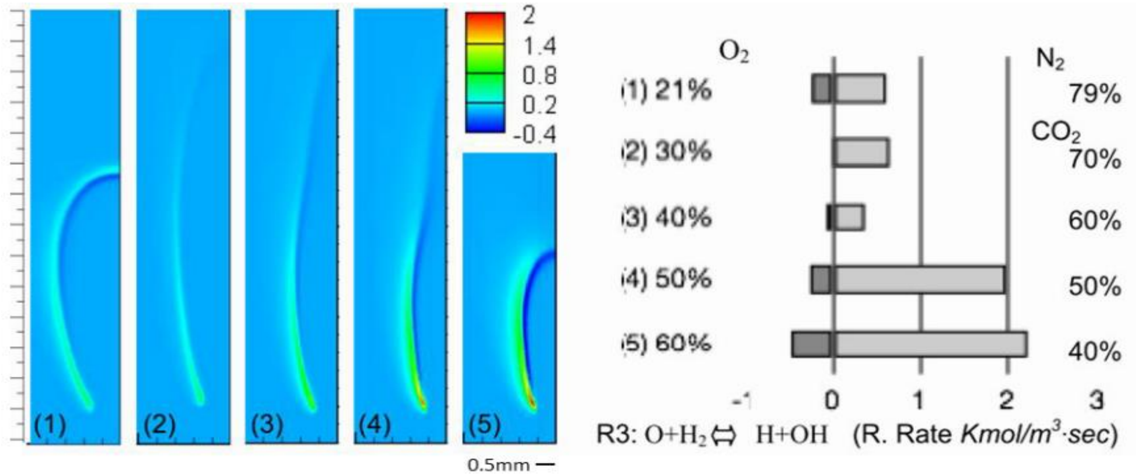

Fig.4 Simulated reaction rates of R3: $O+H_2 \leftrightarrow H+OH$ (R. Rate Kmol/m^3·sec) with coflow at various conditions.

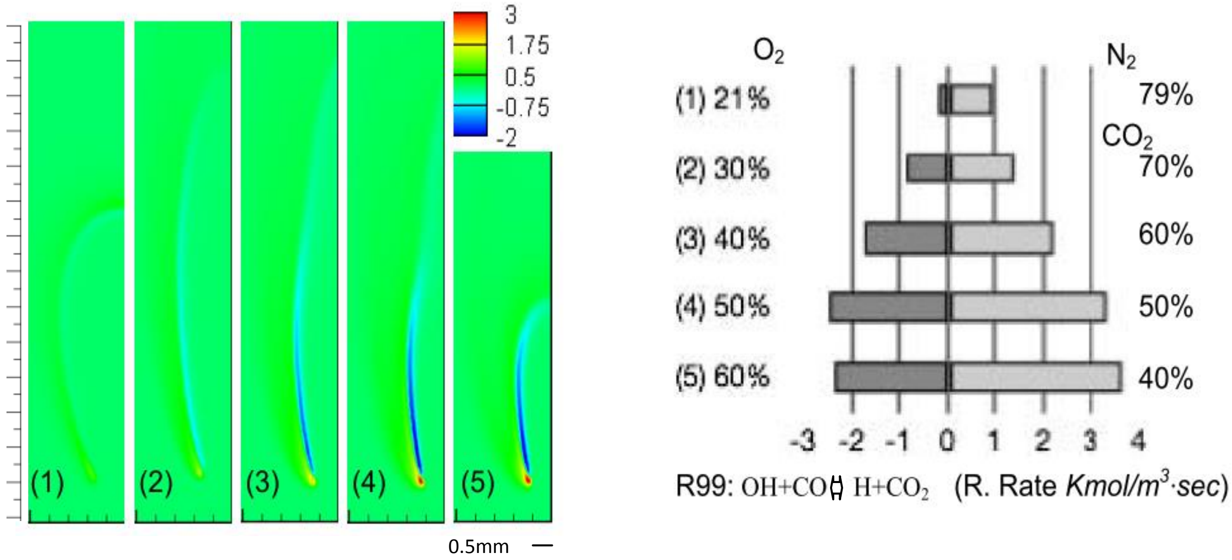

Fig. 5 Simulated reaction rates of R99: $OH+CO \leftrightarrow H+CO_2$ (R. Rate Kmol/m^3·sec) with coflow at various conditions.

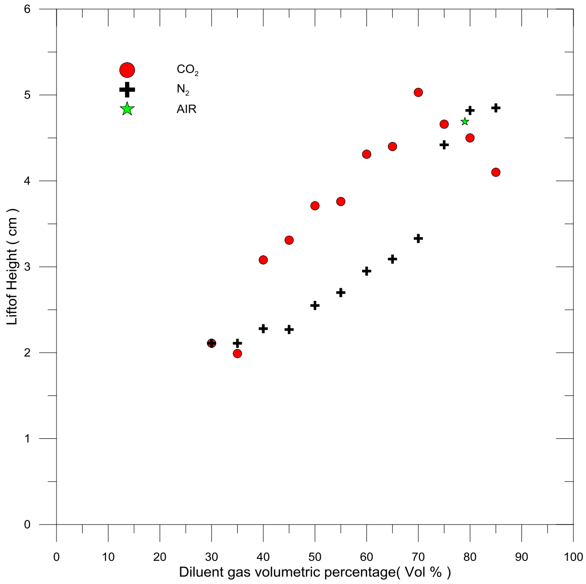

Fig.6 The liftoff height of methane jet flame with different diluent at various conditions.

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