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Experimental and Numerical Study of Oxygen Diluted Partially Premixed Dimethyl Ether/ Methane Counter Flow Flame

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The oxygen diluted partially premixed dimethyl ether/methane counter flow flames were discussed in this paper. Flame images and flame structures were obtained through experiments and numerical simulation. Flame propagation velocity of premixed fuel and emissions were investigated over wide range of DME blending ratios. The methane / dimethyl ether ratio is varied from 1 to 0, while the premixed equivalence ratios of fuel-side and oxygen concentrations are unchanged. In order to exclude the influence of strain rate, the velocities of both sides keep invariable in the experiments and simulation processes and the strain rate are fixed at 49.2 s^{-1}. The results show that the premixed flames are much brighter and flame surfaces are becoming thicker with the increase of DME blending ratios, in addition, the flame surface gradually moves to the premixed side and the spacing between the double flames is increased. With the increase of the proportion of DME, the flame propagation velocities gradually increase, but they are not linearly related, that is the growth rate of flame propagation velocity gradually slowed down. For the oxygen diluted partially premixed flame, OH radicals have two peaks in the whole combustion zone, and they are consistent with the two temperature peaks. About two thirds OH radicals are produced in the premixed combustion zone. With the increase of DME blending ratio, temperature distributions are higher and the raised flame temperatures accelerate the produce of thermal nitrogen oxide, resulting in increase of NO emissions.

1. Introduction

In the last two decades years, a lot of worldwide researchers investigated the combustion characteristics and performance of alternative and renewable fuels. Among these, Dimethyl ether (DME) has been regarded as a promising substitute not only because it is the simplest ether, but also because it has no carbon-carbon bond and high oxygen content, making it soot-free combustion (Yu et al., 2014).

Kaiser et al. (2000) investigated the species profiles of two different equivalence ratios DME–air flat flames experimentally and numerically using the mechanism of Fischeret et al. (2000). Results showed that the CH_2O mole fractions were 5 – 10 times larger in DME flames when compared to methane flames of similar equivalence ratios. Zheng et al. (2005) studied the ignition of nitrogen-diluted DME by counter flowing it against heated air at pressures from 1.5 to 3 atm.

DME is also a good additive. Experiments and simulations were performed to investigate partially premixed combustion using different types of fuels with DME, including methane (Lowry et al., 2011), methanol (Chen et al., 2009), n-butane and propane (Lee et al., 2011). Among these, the most widely used blending fuel is DME/methane binary fuel because of potential low emissions. Chen et al. (2007) experimentally and numerically studied the effect of DME addition in methane/air mixtures. He discovered that DME significantly decreased the high temperature ignition delay and increased the flame speed. Lowry et al. (2011) investigated the laminar burning characteristics of DME/methane binary fuel at 20 % and 40 % DME mixing ratios and various initial pressures. Their results indicated that the flame speed was increased with DME addition.

There are many ways to study the flame structure and characteristics of laminar flame, including standard tube, constant volume, counter flow flame, plane flame and Bunsen lamp method. The counter flow flame method is used most widely because of its stability of flame surface, the same degree of stretch rate, easy to post-measurement and analysis. In this paper, the oxygen diluted partially premixed dimethyl ether/methane counter

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flow flames were used to investigate flame propagation velocity and emissions over wide range of DME blending ratios.

2. Experimental and computational approaches

2.1 Experimental apparatus

In the counter flow experiments, the flow equalization of nozzle outlet flow is the basic of the experiments, and the nozzle design has a direct impact on the flow equalization effect. Therefore, the nozzle design and selection is a very important part. Figura and Gomez (2014) used the shrink round nozzle, as the counter flow device, finding that flow equalization of shrink nozzle is better in the center of the flow, but it is easy to cause the flame overflow in the outside of the nozzle. Lockett et al. (1999) found that, with the circular nozzle, the centre of premixed flame would be raised when the equivalence ratio was low, and the flame surface would not be one-dimensional. Kim et al. (2014) changed the conventional circular nozzle structure, with using a rectangular nozzle to build a linear counter flow experimental device. He found that the flames of various conditions can show satisfied quasi-one-dimensional characteristics. Compared with the circular nozzle, the rectangular one can be used in the wider equivalence ratio range, so the rectangular nozzles are used as the counter flow device in this paper.

The line-oriented counter flow flame experimental device is shown in Figure 1, the nozzle outlet width 30 mm, height 10 mm, relative distance 30 mm. In order to achieve a better flow equalization effect, a filter and a honeycomb ceramic are placed in the concave of the inlet downstream. The device was covered with quartz glass, using of dimethyl silicone oil to produce adsorption, to ensure the sealing requirements.

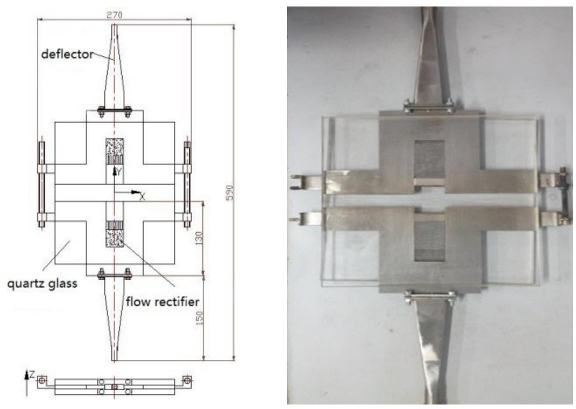


Figure 1: Schematic diagram of the experimental apparatus

2.2 Experimental methodology and operational parameter

The stretch rate is the velocity gradient in the vertical direction of the flame surface, and it has a large effect on the flame pattern. Therefore, the velocity of both sides is fixed in this paper to ensure that the stretch rate is constant, which is expressed by the Eq(1). Here U_f and U_o are the velocity on each side, and d is the separation distance between the nozzles. In the experiment, the methane / dimethyl ether ratio is varied from 1 to 0, while the premixed equivalence ratios of fuel-side and oxygen concentrations are unchanged. The experimental conditions are shown in Table 1, where subscript o indicates the oxidizer-side, and subscript f indicates the fuel-side.

Table 1: Experimental conditions

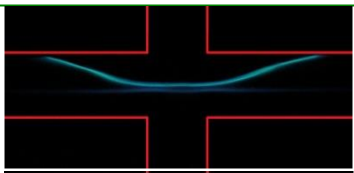
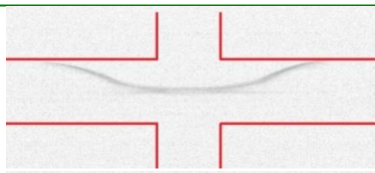
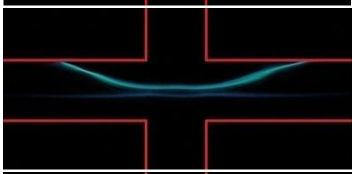
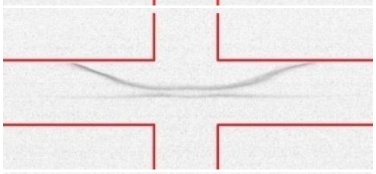
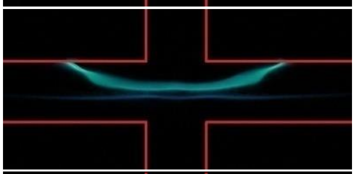
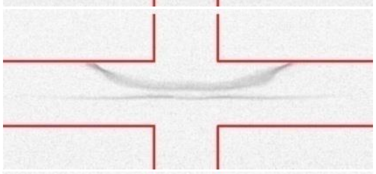
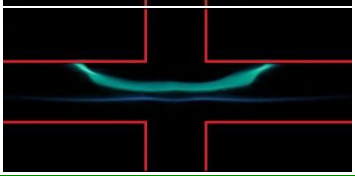
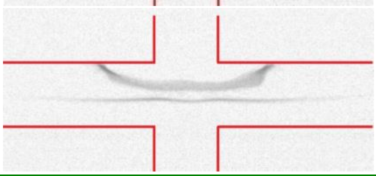
case	Methane/ dimethylether	Equivalence ratio Φ_f	O_{2f} (%)	U_f (m/s)	O_{2O} (%)	U_O (m/s)	Nozzle spacing d (mm)	Stretch rate K (s^{-1})
1	1:0	1.1	18	1.068	26	0.408	30	49.2
2	3:2	1.1	18	1.068	26	0.408	30	49.2
3	2:3	1.1	18	1.068	26	0.408	30	49.2
4	0:1	1.1	18	1.068	26	0.408	30	49.2

$$K = (U_f + U_o) / d \tag{1}$$

2.3 Experimental images

The flame images, shown in Table 2, are measured with Canon EOS 5D Mark II DSLR camera. The camera lens is 1 meter away from the flame. The exposure time is set to 1/5 seconds, and the position of the camera bracket is fixed at each case. The flame temperature profile is measured with B type thermocouple. The thermocouple probe diameter is 0.4 mm and it can be used under 2,200 K with measurement accuracy at 0.5 %t. It is shown clearly that all flames have distinct double flame structures. It is worth noting that with different DME blending ratios, their flame structures have obvious difference. With the increase of DME blending ratios, the upper part flame (fuel- side) is much brighter and flame surfaces are becoming thicker, in addition, the flame surface gradually moves to the premixed side and the spacing between the double flames is increased. From the CH radical distributions, it can be seen that, the methane pyrolyzes completely in the nonpremixed combustion zone when pure methane as a fuel, and CH radicals increased gradually with the increase of DME blending ratios.

Table 2: Flame images and CH distribution at different fuel ratios

case	Methane/ dimethylether	Flame images	CH distribution
1	1:0		
2	3:2		
3	2:3		
4	0:1		

2.4 Experimental methodology and operational parameter

Computations were performed with the opposed flow flame code, OPPDIF, using Zheng mechanism with the recommended multi component transport and thermo chemical database. The boundary conditions at the inlets included measured inlet temperature, velocity, and the species flux, shown in Table1. Figure 2 shows predicted temperature distributions and comparisons of predicted temperature with the corrected measured data. Since the deviation caused by radiative losses should be considered, temperature corrections can be calculated according to Eq(2), which is deduced from the heat balance equation of thermocouple junction. Here T_{mc}, T_m, T_w are corrected measured, measured, and ambient temperature. ε is the thermocouple surface emissivity. σ is Stefan-Boltzmann constant. D_c is the probe diameter. K_f is the thermal conductivity of flue gas.

$$T_{mc} = T_m + \frac{\varepsilon \sigma D_c}{K_f \cdot \left(2 + 0.6 \cdot \mathrm{R}_e^{0.5} \cdot \mathrm{Pr}_f^{0.33}\right)} \left(T_m^4 - T_w^4\right) \tag{2}$$

It is shown that the simulation results predict the trend of combustion temperatures well. However, the measured highest temperature is a little lower than the simulation results. The reason is that amount of heat dissipation was carried away by nitrogen and quartz glass, which is not considered in the simulation.

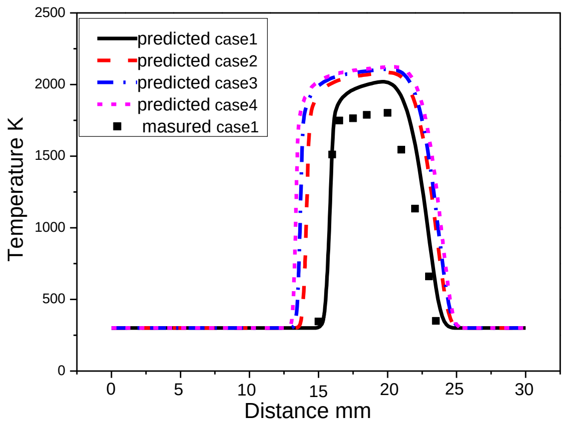


Figure 2: Temperature distributions

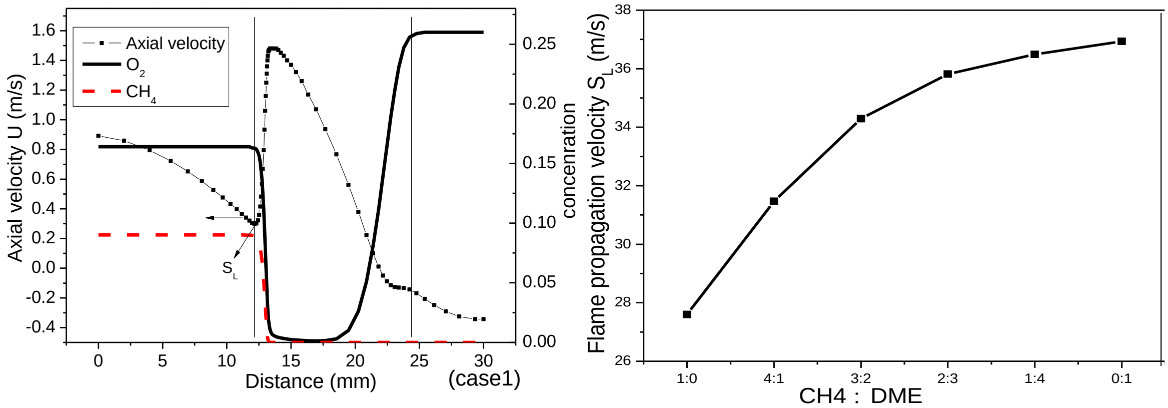
3. Results and discussions

3.1 Flame propagation velocity

In the case of pure methane combustion, for example, as shown in Figure 3(a), when the gas flows out of the nozzle, the gas flow rate decreases continuously due to the expansion of the flow field, and the axial velocity gradually increases when the flow rate decreases to a certain value.

From this minimum velocity, the methane and oxygen concentrations begin to decrease, demonstrating that the premixed gas enters the premixed combustion zone where it begins to burn, at which time the airflow velocity is increased. At this point the air velocity and the flame propagation velocity are balanced, so the minimum velocity of the airflow is the flame propagation velocity here S_L, and the local stretch rate at the upstream is K_i.

The flame propagation velocity at different methane / dimethyl ether blending ratios is shown in Figure 3(b). It can be found that with the increase of the proportion of DME, the flame propagation velocity gradually increases, but they are not linearly related. With the increase of DME blending ratio, the growth rate of flame propagation velocity gradually slowed down.

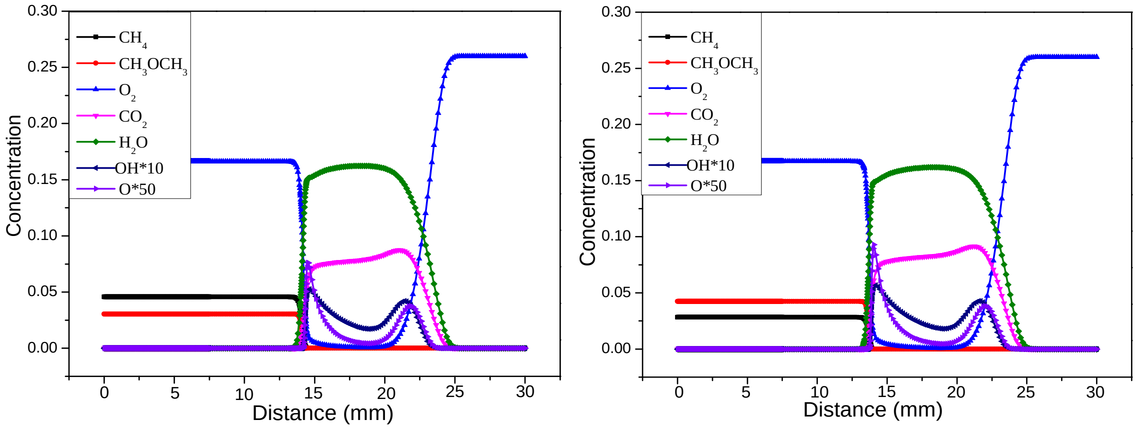


(a) distribution of axial velocity (b) flame propagation velocities at different fuel

Figure 3: Flame propagation velocities

3.2 Flame structure

Figure 4 shows the simulated fuel consumption and some important chemical species profiles (O_2, CO_2, CO, H_2O, OH, O) with different DME blending ratios. They have distinct double flame structures. Some intermediate products (e.g. CO) are generated in the fuel-rich side and the position of CO concentration peak is consistent with that of temperature peak in the premixed combustion zone. OH radicals have two peaks in the whole combustion zone, and they are consistent with the two temperature peaks. About two thirds OH radicals are produced in the premixed combustion zone.



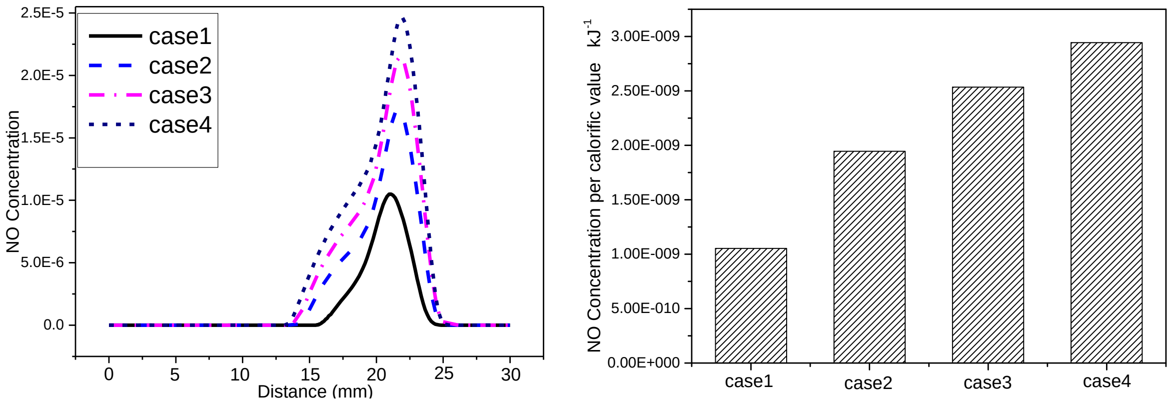
(a) case 2 (b) case3

Figure 4: Flame structures

3.3 NO emission

The distribution of NO concentration at different methane / dimethyl ether blending ratios is shown in Figure 5(a). It can be found that with the increase of the proportion of DME, the peak of NO concentration increases gradually, and the range of NO formation field increases too. The NO concentration peak appears at the peak of the temperature. In addition, the NO concentration in the premixed combustion zone is much lower than in the nonpremixed combustion zone, the reason is that the oxygen concentration of the oxidizer-side is 26 %, much more than 21 %.

In this paper, in order to ensure the same flow rate and equivalence ratio, the fuel and calorific value are different with different methane / dimethylether blending ratios. The NO concentrations per calorific value are compared in Figure 5(b), and it can be found that with the increase of the proportion of DME, NO emissions are still increased.



(a) NO concentration distributions (b) Total NO concentration per calorific value

Figure 5: NO concentration at different fuel ratios

4. Conclusions

Experimental and simulation work had been conducted to study one-dimensional oxygen diluted partially premixed dimethyl ether/methane counter flow flames in this paper. Flame propagation velocity of premixed fuel and emissions were investigated over wide range of DME blending ratios. In order to exclude the influence of strain rate, the velocities of both sides keep invariable in the experiments and simulation processes. The main results can be summarized as follows.

(1) With the increase of DME blending ratios, the premixed flames are much brighter and flame surfaces are becoming thicker, in addition, the flame surface gradually moves to the premixed side and the spacing between the double flames is increased.
(2) With the increase of DME blending ratios, the flame propagation velocity increases, while the growth rate of flame propagation velocity gradually slowed down.
(3) OH radicals have two peaks in the whole combustion zone, and they are consistent with the two temperature peaks. About two thirds OH radicals are produced in the premixed combustion zone.
(4) With the increase of the proportion of DME, NO emission per calorific value increases gradually, and the range of NO formation field increases too.

Acknowledgments

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