Characteristics of Laminar Premixed H_2/CO/CH_4/Air Opposed-jet Flames

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1 Introduction

Extensive fossil fuel consumptions have resulted in rapid fuel depletion as well as atmospheric and environmental pollutions. In order to reduce these impacts, two alternatives are currently considered: either to improve the combustion efficiency with considerable reductions in the pollutant emissions into the atmosphere, or more significantly, to replace fossil fuel usage as much as possible with environmentally friendly, clean and renewable energy sources [1]. Among the various renewable energy sources, the use of gasified biomass that contains a mixture of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen, can be more versatile and attractive. It becomes essential, therefore, to develop combustion techniques that can burn the gasified biomass or low-grade syngas effectively and to understand chemical and physical properties of flames for such kind of fuels. Since the combustion characteristics of blended fuels may differ substantially from those of single-component fuels, therefore, the detailed investigations of flame structures and chemical kinetics of blended fuels are of vital importance. The effect of H_2 concentration on the laminar burning velocity of methane–hydrogen-air flames has been reported extensively [2-4]. Moreover, the effects of H_2 or CH_4 additions on the propagation and extinction of atmospheric CO/air opposed-jet flames were experimentally and numerically studied [5]. The effects of CO addition on the characteristics of laminar premixed CH_4/air opposed-jet flames were investigated by the authors [6]. Literature survey indicates that no detailed investigation on the characteristics of H_2/CO/CH_4/air flames has been reported. Therefore, the premixed H_2/CO/CH_4/air flames are studied to delineate its burning phenomena, flame structures, and chemical kinetics.

2 Methodology

The experimental setup is schematically shown in Fig. 1. The opposed-jet burner consists of two water cooled, well-contoured circular nozzles (i.d. = 2 cm) with slow coaxial shielding flows. Two premixed H_2/CO/CH_4/air jets are directed towards each other to form two symmetrical, planar flames. Both

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premixed flames are operated at the fixed stoichiometric condition. The volumetric fraction of H_2 is fixed at 10% and 20%, while CO and CH_4 are varied in the blended fuel. The separation distance between two nozzles is 2 cm and the bulk velocity at each jet exit is maintained at 2 m/s for the present study. Research-grade fuels and compressed air are metered by electronic mass flowmeters and mixed in a mixing chamber prior to the opposed-jet burner. The flame is shielded from ambient air by a nitrogen coaxial flow with low velocity, which is controlled using a rotameter. The experimental conditions of the premixed stoichiometric H_2/CO/CH_4/air opposed-jet flames are listed in Table 1. In experiments, the visible flame features are obtained using a high sensitivity 3-chip color CCD camera (Sony DXC-9000) and digitized by the frame grabber for further digital image processing to identify the flame front position. An R-type (Pt/Pt–13Rh) thermocouple with 25 μm wire diameter is used to measure the flame temperature. BeO and 10–15% Y_2O_3 coating is applied to eliminate catalytic reactions induced by platinum in the flame. The measured temperature in the flame is corrected for radiation heat loss by assuming a spherical thermocouple bead.

The adiabatic, unstrained, free propagation velocities of the laminar premixed H_2/CO/CH_4/air flames are calculated using the PREMIX code of Chemkin collection 3.5. On the other hand, the flame structures of the premixed stoichiometric H_2/CO/CH_4/air opposed-jet flames are simulated using the OPPDIF package with the GRI-Mech 3.0 chemical kinetic mechanisms [7] and detailed transport properties. For the opposed-jet flame calculations, the computation domain and input parameters for each flame condition are in accordance with experiments. The adaptive regridding method is applied to solve the flame structure, and the grid independence of the solutions is achieved by tuning the GRAD and CURV parameters in the package. The number of grid lines is set to more than 400 for each case. The minimum grid dimension is approximately 0.1 μm, which is sufficient to resolve the flame thickness and the steep temperature gradient.

3 Results and Discussion

The computed laminar burning velocities of the premixed stoichiometric H_2/CH_4/CO/air flames with 10% and 20% H_2 and various CO/CH_4 fuel compositions are shown in Fig. 2. Note that the laminar burning velocity is also calculated based on the "dry" oxidation condition, i.e., no water vapor is present in the air. Fig. 2 shows that the laminar burning velocity increases with increasing H_2 in the fuel mixture. When 10% of H_2 is added to the fuel mixture, the laminar burning velocity increases with increasing the CO content in the CO/CH_4 mixture. The maximum burning velocity (60.7 cm/s) occurs at the condition of 10% H_2–(90% CO+10% CH_4). Note that the burning velocity has increased from near zero for the pure CO flame to a value of 46.7 cm/s for the 10% H_2–(100% CO+0% CH_4) flame. In addition, the increase of H_2 content in the blended fuel not only increases the burning velocity, but also shifts the maximum burning velocity from that occurred at 90% CO+10% CH_4 for 10% H_2 to 94% CO+6% CH_4 for 20% H_2. Fig. 2 indicates that the laminar burning velocity is not only infuenced by the content of H_2, but also by the CO concentration in the fuel mixture. This fact suggests that further investigations of the flame and chemical kinetic structures of the premixed stoichiometric H_2/CO/CH_4/air flames are needed.

Photographs of the premixed stoichiometric H_2/CO/CH_4/air opposed-jet flames with 10% and 20% of H_2 and various CO contents in the fuel mixture are shown in Fig. 3. As the CO concentration is increased, the postflame zone (region between two plannar flames) immediately becomes orange in color and extends in lateral direction. It is noted that the separation distance between two symmetrical flames increases with increasing CO concentration. The separation distance reaches to a maximum value at the conditions of 90% CO–10% CH_4 and 94% CO–6% CH_4 for 10% and 20% of H_2 additions, respectively. Fig. 3 also indicates that the increase of H_2 addition to the CH_4/CO/air mixtures increases the separation distance and changes the flame front position.

Comparisons of the measured and predicted temperatures for the flames with 10% and 20% of H_2 additions and various CO and CH_4 contents are shown in Fig. 4. For temperature measurements, due to the limitation of the R-type thermocouple (~2040 K) only the preheated and partial oxidation zones are measured. Fig. 4 shows that when 10% and 20% of H_2 are added to the fuel mixture, the preheated

zone closest to the nozzle exit occurs at the condition of 90% CO–10% CH_4 and 94% CO–6% CH_4, respectively. The predicted flame temperatures are in good agreement with the measured data for all the flames measured.

In order to understand the effect of the variation of blended fuel composition on chemical kinetic structure, the calculated profiles of net reaction rate of the six major elementary steps (R38: $H + O_2 \leftrightarrow OH + O$, R46: $HO_2 + H \leftrightarrow OH + OH$, R53: $H + CH_4 \leftrightarrow H_2 + CH_3$, R84: $OH + H_2 \leftrightarrow H + H_2O$, R98: $OH + CH_4 \leftrightarrow CH_3 + H_2O$, and R99: $OH + CO \leftrightarrow H + CO_2$) along the jet axis are plotted in Fig. 5 for flames 5 and 8. Here the calculated results are presented for two flames only, due to space limitations. It can be seen that the most significant reaction is the chain-branching reaction (R38) followed by the OH attack on H_2 through reaction (R84), as the CO concentration in the fuel mixture is low. When the CO is increased to 78.4%, the rate of reaction (R46) for OH production and the rate of reaction (R99) for CO oxidation exceed that of reactions (R98) and (R53) for the dehydrogenation of methane.

4 Conclusions

The combustion characteristics of the stoichiometric, premixed H_2/CO/CH_4/air opposed-jet flames are experimentally and numerically investigated. Results show that the predicted flame temperatures and their spatial distributions are in good agreement with the measured data. The calculated laminar burning velocity indicates that the maximum value occur at the condition of 90% CO–10% CH_4 and 94% CO–6% CH_4 for 10% and 20% of H_2 additions, respectively. Finally, we found that the reaction $OH + CO \leftrightarrow H + CO_2$ plays an important role in H_2/CO/CH_4/air flames.

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Table 1: Experimental conditions of the premixed stoichiometric flames

Flame No.	H_2/CO/CH_4 Fuel mixture (vol %)			CO/CH_4 Fuel mixture (vol %)		Air (vol %)
	H_2	CO	CH_4	CO	CH_4	
1	10	9	81	10	90	89.09
2	10	45	45	50	50	84.83
3	10	81	9	90	10	75.14
4	10	88.2	1.8	98	2	71.50
5	20	8	72	10	90	88.26
6	20	40	40	50	50	83.96
7	20	75.2	4.8	94	6	73.14
8	20	78.4	1.6	98	2	71.38

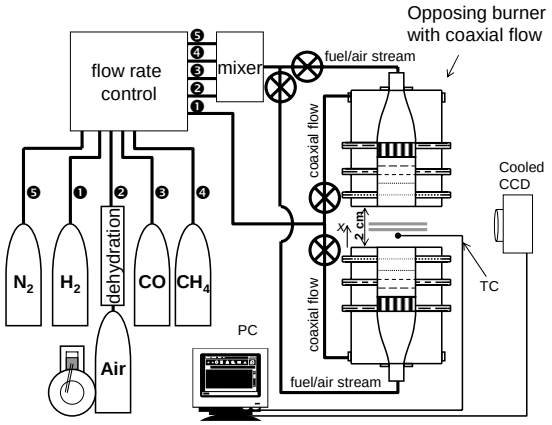

Fig. 1. Experimental apparatus of the fuel supply system and opposed-jet burner.

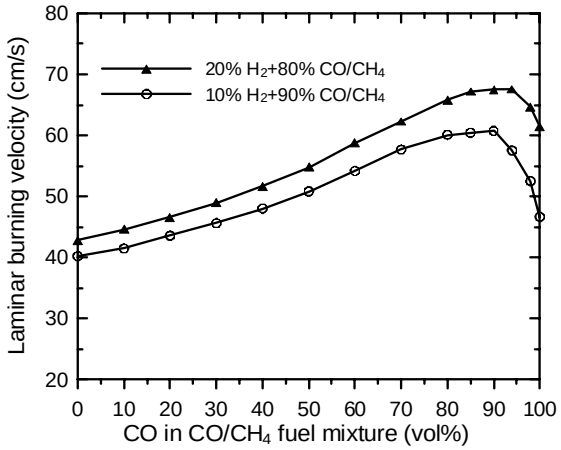

Fig. 2. Computed laminar burning velocity of the stoichiometric H_2/CO/CH_4/air flames as a function of CO contents in the CO/CH_4 fuel mixture with 10% and 20% H_2 additions.

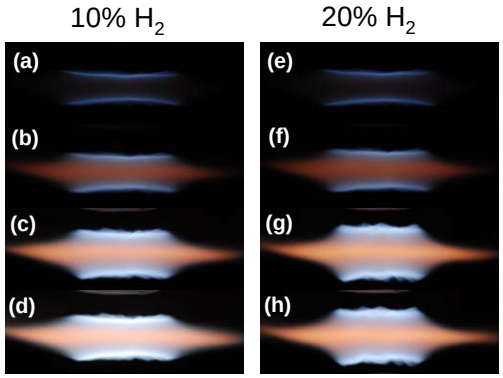

Fig. 3. Photographs of the premixed opposed-jet flames. (a): flame #1, (b): #2, (c): #3, (d): #4,; (e): #5, (f): #6, (g): #7, (h): #8.

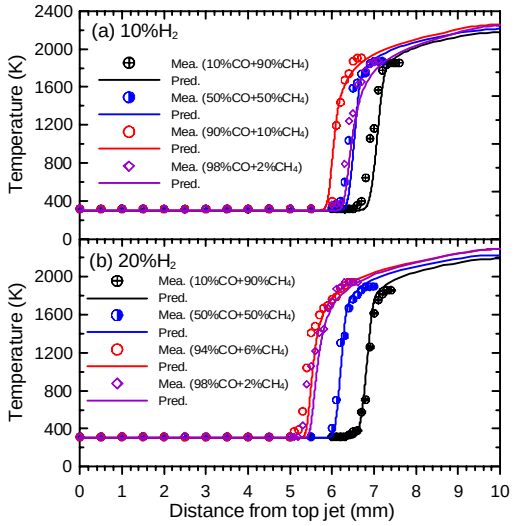

Fig. 4. Comparison of the measured and calculated flame temperatures for the premixed stoichiometric H_2/CO/CH_4/air flames: (a) 10% H_2 and (b) 20% H_2.

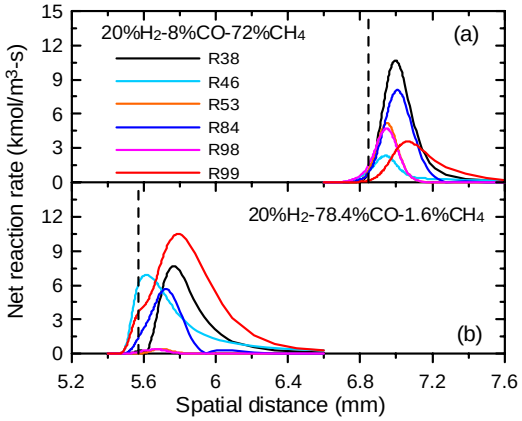

Fig. 5. Computed axial distributions of net reaction rate for flames 5 and 8.