Investigations of Blended CH_4/CO Premixed Jet Flames– Experimental Measurement and Numerical Validation

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1 Introduction

It is believed that detailed knowledge of fundamental flame properties is essential for practical application, as well as design optimization for emission and CO_2 reduction. Recently, since the application of the Kyoto protocol, more stringent regulations on energy conversion systems have been extensively posed in most of developed and developing countries and these stringent regulations indeed drive advanced combustion research for clean and environmentally friendly use of the fuel. Biomass including renewable and short carbon-cycle fuels such as gasified biomass, gasified coal gas and low-grade syngas are now seriously considered as one of the major candidates of alternative fuels [1]. However, some basic technological problems remain to be solved regarding the combustion of gasified biomass. For instance, the general flame structure, the burning velocity and the definition of Lewis number and the associated flame front instability of the gasified biomass flame as it usually contains methane, hydrogen, carbon monoxide, as major species. It becomes important to carefully investigate into the oxidation phenomena of the gasified biomass and to develop combustion techniques to burn the gasified biomass or low-grade syngas effectively.

It is well known that carbon monoxide is a major species in gasified biomass fuels and a major intermediate of hydrocarbon flames. Relatively few researches have attempted to investigate the flame structure and associated reaction mechanisms [2] –[5]. On the other hand, for the basic phenomena of CH_4/CO/air premixed jet flames, no detailed investigation have been proposed. In addition, the flow fields, mass transport properties as well as the flame structure are still not clearly understood. In view of the above considerations, the combustion behaviors of artificially blended CH_4/CO/air premixed jet flames are studied by using both experimental and numerical methods in the present study. The obtained results can be used to further delineate the design and operational issues and to facilitate practical information for the design of effective gasified biomass combustors.

2 Methodology

Among the various characteristic combustion configurations, the jet flame, which contains essential flame characteristics in a simpler form, is usually used for the basic studies of flame/flow related phenomena such as the interaction between flow and reacting processes, instability, blowout limits etc. In the present study, experiments are carried out on a jet burner consisting of a 10 mm-diameter circular contoured nozzle, from which mixture emerges.

Table 1 Experimental Condtions

Flame	Fuel		Mixture	Exit velocity(m/s)
	CH_4 (vol%)	CO(vol%)	Air(vol%)	
1	100	0	90.49	2.0
2	90	10	89.80	2.0
3	80	20	89.00	2.0
4	70	30	88.06	2.0
5	60	40	86.95	2.0
6	50	50	85.61	2.0
7	40	60	83.96	2.0
8	30	70	81.89	2.0
9	20	80	79.20	2.0
10	10	90	77.53	2.0
11	0	100	70.41	2.0

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Fuels and air are metered by electronic flowmeters. All electronic meters are carefully calibrated. The mixture passes through a settling chamber to rectify the flow quality and was burned through the nozzle. The nozzle wall was contoured with fifth-order polynomial profiles, and the area contraction ratio is 400. Honeycombs and fine mesh screens are installed in the settling chamber to manage the flow quality. The stream at the nozzle exit exhibited a top-hat velocity profile, and the turbulence intensity at the centerline is about 0.5%. The experimental conditions of premixed jet flames are listed in Table 1.The flame temperature is obtained intrusively by an R-type (Platinum and Platinum with 13% Rhodium) thermocouple with 25μm diameter which is spot-welded to the 125 μm supporting wires. The Beryllium oxide (10-15%) and Yttrium oxide mixture coating is applied to eliminate the surface-catalyzed radical recombination reactions effect of platinum in flame. For flow velocity measurement, digital particle image velocimetry (DPIV) is applied. The wavelength and pulse energy of the laser (LS-2134U, LOTIS TII Ltd.) light are set as 532nm and 180mJ respectively. A high-resolution, high sensitivity, and low dark current SharpVision 1300DE camera manufactured by IDT is used for images recording. The image array of CCD is 1280×1024, and pixel size is 6.7μm×6.7μm. The spatial resolution of CCD with proper lenses is 12.5μm/pixel, and the delay time between two laser pulses is 50 μs. For identification of the reaction zone, the laser-induced predissociative fluorescence (LIPF) of OH molecules from $v'' = 0$ to $v' = 3$ in the $A^2\Sigma \leftarrow X^2\Pi$ system is employed. The laser beam spreads into a thin sheet of 34 mm height and 0.2 mm thickness by a single cylindrical lens (f = 1000 mm) and intersects vertically through the flame axis. Only the 25mm central portion of the laser sheet, where the laser intensity is high and uniform, is used for imaging. The OH fluorescence signal is imaged onto an intensified CCD camera (576 × 384 pixels) with a UV camera lens (Nikkor, *f* = 105 mm, *f*/4.5). A 10-mm thick butyl acetate liquid filter is placed in front of the camera to remove the Rayleigh scattering. The OH fluorescence signal is collected at 297 nm, corresponding to the fluorescence produced from the 3 → 2 transitions.

To numerically model the CH_4/CO/air premixed jet flames, the governing equations of mass, momentum, energy, and chemical species for a steady axisymmetric reacting flow are solved using commercial package CFD-ACE. An orthogonal, non-uniform staggered-grid system is used for solving the discretized equations with a control volume formulation in accordance with the SIMPLEC algorithm. The GRI-mech 3.0 [6] full mechanism is coupled to the CFD package and employed in the present study to investigate flame structures. Moreover, the comparison between simulated and measured results is also performed to verify the validity of numerical simulation in this work.

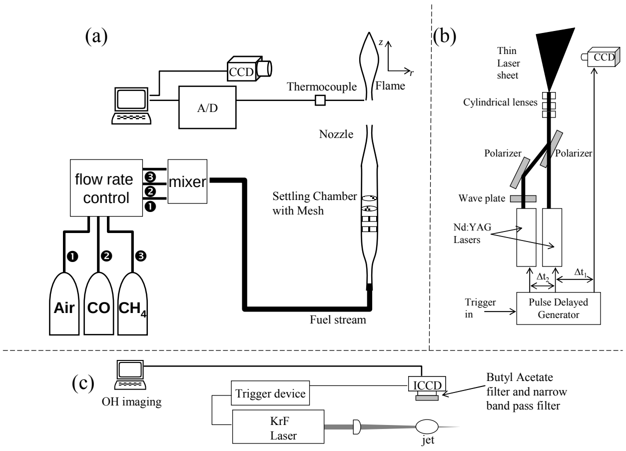

Fig. 1 Experimental Setup: (a) Essentials of the experimental arrangements; (b) Arrangements of lasers and optics of PIV device; (c) Schematic setup of 2D LIPF.

3 Results and Discussion

Direct photographs of jet flames are shown in Fig. 2, in which correspond to different mixing levels of CO with CH_4. The premixed stoichiometric mixture emerges from a circular jet. In Fig. 2(#1), from appearance, the whole flame of 100% CH_4 premixed jet is blue and the premixed cone can be found clearly. For pure CO premixed flame, the silvery bright white emission from flame can be found in Fig. 2(#11). It is interesting to note that the postflame zone becomes yellow in color, and the top angle of flame cone is decreased with the concentration of carbon monoxide is increased (Figs. 2 (#2 ~ #10)). The top angle of the flame cone reaches a minimum value in the condition of flame #10 (10% CH_4-90% CO). In addition, the top angle of the flame cone can also be identified as well in pure CO premixed flame and its value is close to that of pure CH_4.

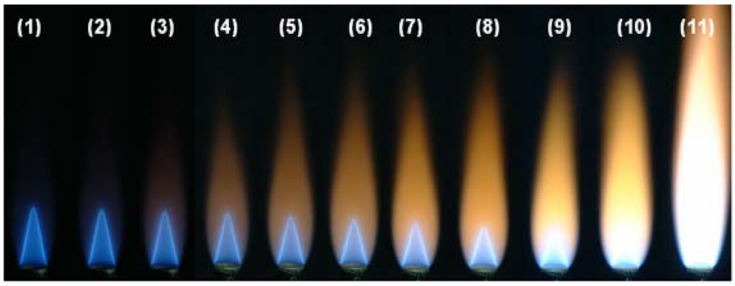

Fig 2 Photographs of stoichiometric premixed jet flame corresponding to Table 1 (shuttle time = 1/250 sec)

Since the present study deals with the simulations of CH_4/CO blended fuel by using GRI-mech 3.0 [6] which has been optimized for methane and natural gas, careful experimental validations for blended fuels are necessary. Photographs, planar LIF imaging as well as the simulated OH concentration near flame cone of the premixed jet flame corresponding to flame #2, #8, and #10 are shown in Fig 3. The results demonstrate that the present numerical simulations can excellently reproduce experimental observations in flame shapes of potential cone.

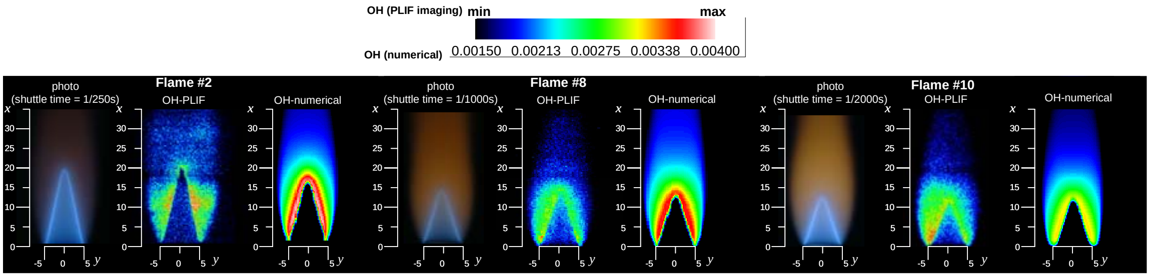

Fig. 3 Photograph, planar LIF imaging, and computed OH contour for flame #2, #8, and #10

In order to further verify the present simulation, simultaneous planar flow velocity measurements are performed by using digital particle image velocimetry. Two Mie scattering images of particles near the flame cone are shown in Fig. 4(a) and 4(b). The images are snapshot photographs taken at the time of the first and second laser shots respectively. The corresponding spatial resolution is 79 pixel/mm, and the time interval between the consecutive two shots is 50 μs. In the reaction zone, due to high temperature, the gas density decreases by a factor of 7 and the scattering cross-section of the seeding particles reduces drastically when pass the reaction zone [7]. This problem may affect the accuracy of velocity measurement. Through proper digital pre-processing of images, errors can be reduced. The evaluated velocity vectors are shown in Fig. 4(c). Due to the noise in the reaction flow, some incorrectly determined vectors can usually be found by visual inspection. These errors can be further eliminated by using data validation and outlier replacement algorithms in the digital post-processing. Fig. 4(c) also shows the resultant streamline in this domain, and the measured streamlines show the general flow characteristics near flame cone. Based on the PIV measurements, the velocity distributions in premixed jet flame can be calculated through proper image optimization and post processing algorithms.

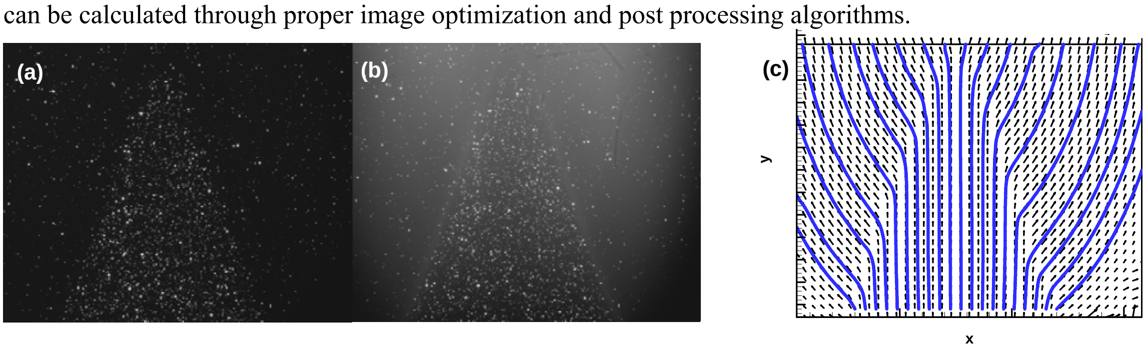

Fig. 4 Snapshot photographs taken at the time of the first (a) and second laser shots (b); evaluated velocity vectors (c) for flame #10

To be more precise, the comparison of measured velocity along jet axis from x = 5 to 25 with the calculated results using detailed reaction mechanisms for flame #10 are shown in Fig. 5(a). Similar comparison of the computed and measured radial profiles of velocity for the flame at x = 5mm are shown in Fig. 5(b). The experimental data are indicated by symbols and solid lines denote those from the simulation. It can be seen that the calculated flow velocity is in good agreement with the experimental data via PIV measurement.

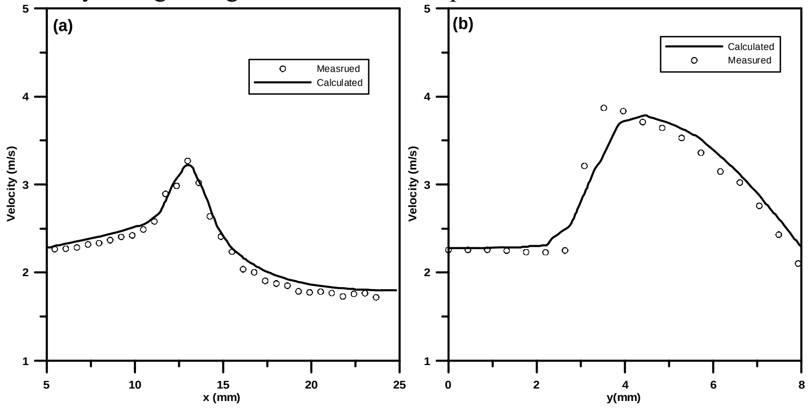

Fig. 5 Comparison of the measured and computed axial (a) and radial (b) (at x = 5mm) velocity profiles for the flame #10

4 Conclusion

The combustion characteristics of the stoichiometric, premixed CH_4/CO/air jet flames are experimentally and numerically studied. The flame structures are calculated using the CFD-ACE coupled with multi-component transport model and GRI-Mech 3.0 chemical kinetic mechanisms. Results show that the predicted flame geometry and flow field are in good agreement with the laser diagnostic measurement data.

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