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Research Paper

Combustion characteristics of non-premixed methane micro-jet flame in coflow air and thermal interaction between flame and micro tube

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HIGHLIGHTS

- The flammable region of methane micro-jet flame in coflow airs was measured.
- OH and CH distributions of the methane micro-jet flames were obtained.
- The heat exchanges through different surfaces of the solid micro tube were clarified.
- The fuel stream in the tube is preheated by the flame through thermal interaction.
- The preheating effect is significant at a moderate fuel flow velocity.

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ABSTRACT

The combustion characteristics of non-premixed methane micro-jet flame in coflow air were investigated experimentally and numerically. A detailed reaction mechanism was employed in the two-dimension numerical computation. The thermal interaction between the flame and solid tube was considered by using fluid-solid coupled thermal boundaries in the numerical computation. Four typical flames, lifted flame, attached flame, hemisphere flame and umbrella flame, were observed in different fuel flow velocity ranges in experiments. The flame heights, blow off and extinction limits in coflow airs at different velocities were measured. The OH and CH distributions of non-premixed micro-jet flames were obtained by experiments, and the computational results agree well with those from the experiments. The computational temperature distributions show that there are thermal interactions between flames and solid tube. The heat exchanges through surfaces of the solid tube were analyzed in detail. The fresh fuel gas in the solid tube is preheated by the thermal recirculation. Consequently, the combustion intensity of the micro-jet flame is enhanced. The thermal interaction is essentially affected by the flame shape, and it is significant for the hemisphere flame.

1. Introduction

The micro-gas turbine [1–3], micro swing engine [4–7] micro Swiss-roll combustor [8,9], micro-thermophotovoltaic device [10,11] were developed and investigated in the last decade with the increasing demands of energy and power systems in micro and mesoscale. However, it was found that it is difficult to sustain stable flames in the micro combustors due to the increased heat loss and shortened residence time of fuel/oxidizer mixture in the combustor. The fundamental knowledge on combustion characteristics of premixed and non-premixed flames under the micro combustion regime are important for the development of micro-combustion-based energy and power systems.

The combustion characteristics of premixed flames in micro tube and channels were extensively studied, since the premixed flames are widely used in the micro combustors [12–24]. And several procedures have been developed to achieve stable premixed flames under micro scale [25–34]. The heat loss to solid wall is used to preheat the fresh fuel/air mixture in the micro Swiss-roll combustor [8,9], and stable flames were achieved. The investigations of premixed flames in mesoscale channels show that the blow off limits of premixed flames can be enhanced by using bluff bodies [25] and wall cavities [26–30]. The combination of wall cavities with catalytic segments was used to achieve stable premixed

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flame in the micro channel [33,34]. The previous studies suggest that the thermal interaction between the micro flame and the solid walls has a significant effect on the stability of the micro flame.

The combustion characteristics of non-premixed micro flames achieved by micro tubes have also attracted attentions. The non-premixed propane and methane micro-jet flames in quiescent air have been experimentally studied by Matta et al. [35] and Cheng et al. [36], respectively. The flame height, blow off and quenching flow rates were obtained. The structure and stabilization mechanism of a micro-jet methane diffusion flame near extinction were discussed by Chao et al. [37]. The distributions of temperature and important species of microscale hydrogen diffusion flames have been measured by Cheng et al. [38]. The extinction characteristics of micro-jet flames in quiescent air at normal temperature have been investigated numerically in [39] and theoretically in [40]. The extinction characteristics of methane micro-jet flame in hot air was examined experimentally by Fujiwara and Nakamura [41]. It was found that the heat recirculation through the solid tube enhances the reactivity of the flame. Moreover, the thermal interaction between micro hydrogen flames and micro solid tube was observed in a recent numerical study which includes the heat transfers between solid and gases [42]. The temperature of H_2 stream is increased by heat recirculation before arriving the tube exit. The heat recirculation through the inner surface of the micro tube was discussed for the cases of using hydrogen, methane and dimethyl ether as fuels [43].

It can be found that the studies on combustion characteristics of non-premixed micro flames using different fuels have already been conducted [35–45]. However, most previous investigations focused on the flame in the quiescent air, and air flow should be adjustable in practical applications. The effect of air flow velocity on the combustion characteristics of non-premixed micro-jet flame deserves more attention. Moreover, the detail of the heat exchanges between flame and surfaces of solid tube needs further investigation.

The combustion characteristic of methane-air non-premixed micro-jet flame is studied in the present work experimentally and numerically. The effect of coflow air velocity on combustion characteristics was investigated and the thermal interaction between the micro-jet flame and the solid tube was analyzed in detail.

2. Experimental system and methods

Fig. 1 schematically shows the experimental system. A stainless steel chamber was used as the main body of the experiment apparatus. Air stream was fed into a rectangular quartz tube, which was connected with the stainless steel chamber. The cross area of the rectangular quartz tube was 10 × 10 cm^2, and the wall thickness was 4 mm. A ceramic honeycomb and ceramic beads were installed in the camber to achieve uniform velocity for the air flow. The gaseous fuel was supplied by a stainless steel fuel tube, which was in the center of the chamber. A stainless steel micro tube with an inner diameter (d) of 280 μm, a thickness of 110 μm and a length of 50 mm was connected with the fuel tube to achieve non-premixed micro-jet flame. The gas flow rates of air and fuel were controlled by digital mass flow controllers (MKS, GE50A series). The digital mass flow controllers were calibrated by wet gas meters (SHINAGAWA, W-NK series) and soap bubble flow meters based on the full scales of the flow controllers before the experiment. The uncertainties of the flow rates of fuel and air were less than 1%. High purity methane (99.99%) was used in the experiments. A single-lens reflex digital camera (Nikon D-300) was employed for the flame image recording. A CH filter (transparent wavelength: 431.4 nm, half bandwidth: 6.4 nm) was used with the single-lens reflex digital camera to capture the CH distributions of flames.

OH-PLIF measurement was conducted to visualize the distribution of the OH radical on the center plane of the flame. The laser system consists of an Nd:YAG laser (Quanta-Ray Pro-230), wavelength of 355 nm, 10 Hz with 10 ns pulse duration and a dye laser (Sirah PSCAN-G-30) with a frequency doubler to excite the $Q_1(8)$ line of the $A^2\Sigma \leftarrow X^2\Pi(1,0)$ bands of OH at a excitation wavelength. The laser goes through the energy monitor and sheet optics to produce a laser sheet. The OH fluorescence was detected by an ICCD camera, located perpendicularly with the laser sheet through a UV lens (Nikon Rayfact PF 10545MF-UV) with an intensified Relay Optics (LaVision VC13-0189) and an OH bandpass filter (LaVision VZ13-0390). The OH fluorescence images were focused onto the CCD chip with the finest resolution of 2048 × 2048 pixels. The CCD camera and Relay Optics were operated with f = 4.5, 200 ns gate width, 120 ns delay, 2000 μs exposure time, 65% in gain and 10 Hz image sampling frequency synchronized with laser. The height of the laser sheet was about 60 mm and the thickness was

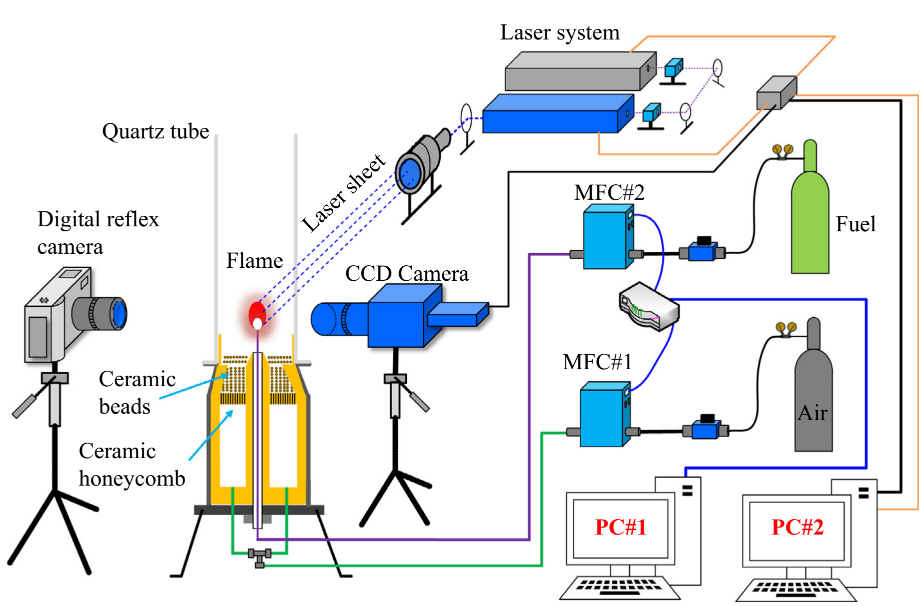

Fig. 1. Schematic of the experimental system.