FLAME PROPAGATION AND QUENCHING IN ULTRA-THIN QUARTZ COMBUSTORS

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Abstract: This paper presents (1) the development of optical measurement system of near-wall OH* concentration in order to investigate the flame quenching mechanism in ultra-thin chamber; and (2) observation and analysis of premixed CH_4/Air flame propagation and quenching in three quartz combustors with chamber depth of 0.7 mm, 1.0 mm and 1.5 mm, respectively. It is found that the quenching distance for heated quartz wall can be smaller than 0.7 mm, and is dependant on the wall temperature. Flammability limits are obtained for different equivalence ratios and mixture velocities.

Key Words: Gas-phase combustion, Ultra-thin quartz channel, Flame quenching, Steady/oscillating flame, Wall temperature

1. INTRODUCTION

Hydrocarbon-fueled micro combustor is of great interest in portable power generation applications for higher energy density [1]. In micro-scale, flame generally quenches in combustors with characteristic length below 3-4 mm due to thermal and chemical quenching near the wall. Catalytic combustion is one of the techniques to realize combustion in micro combustors, but the chamber temperature should be lower than 900°C due to the deactivation of catalyst at higher temperature [2]. Micro-scale gas-phase combustor, if feasible, is beneficial for high temperature applications such as the TPV system.

Maruta et al. [3] investigated the effect of external heat-input and heat recirculation on flame propagation in straight and U-shaped 2-mm-diameter tubes, of which wall temperature is kept at 1120°C. They report that wall temperature is key to tackling the quenching mechanisms. Miesse et al. [4] and Kim et al. [5] separately make quenching distance measurements with different wall materials/treatment, and claim that chemical quenching instead of thermal quenching dominates for high wall temperature. Miesse et al. [4] also found inert materials such as quartz, alumina and cordierite, are effective against chemical quenching. However, the detailed quenching mechanisms in micro-scale still remains unclear due to insufficient experimental evidence. The objective of the present study is to investigate the micro-scale quenching mechanisms through experimental observations of flame propagation and quenching in ultra-thin quartz.

2. MICRO COMBUSTOR & EXPERIMENTAL SETUP

Figures 1 and 2 show the quartz combustor and the experimental setup developed in the present study. Channel height of the upstream section is 0.5 mm, and no flame is expected here. The downstream combustion channel has a height of 0.7 mm, 1.0 mm and 1.5 mm. The inner wall of the combustion channel is made of transparent quartz, so that optical measurements are possible.

(a)
(b)

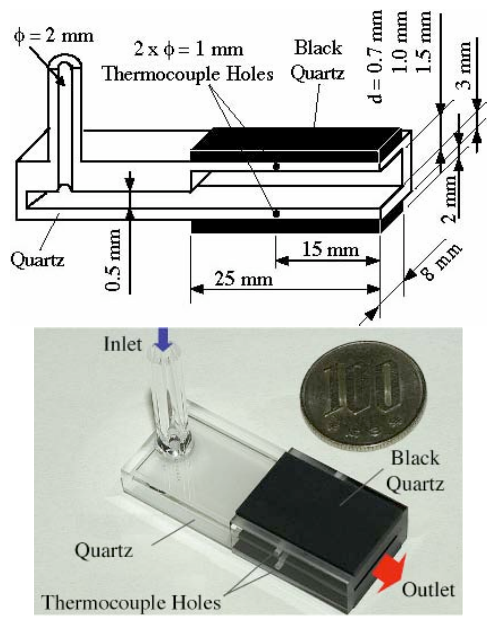

Fig. 1: Micro quartz combustor. (a) Schematic, (b) Photo. Combustion channel is 16 mm wide and 25 mm long. Combustion channel height, d = 0.7 mm, 1.0 mm, and 1.5 mm.

The top and bottom sides of the channel are fusion-bonded with black quartz plates for heating with IR lamp from both sides. The diameter of the heater rod is 20 mm. Two thermocouples are plugged in two 1-mm-diameter holes opened in the transparent quartz layer of the top and bottom walls. Temperature is controlled by manually adjusting the input power of the lamp to keep the thermocouple temperature T_{TC} constant. CH_4 fuel is supplied from a gas cylinder, and air is introduced from a compressor. The CH_4 and air flow rates are separately regulated by two sets of flow meters and valves.

A laser sheet is introduced from the bottom of the combustor as shown in Fig. 2a. An ICCD camera (Flamestar2, La Vision) is placed in the sideway, and OH* chemiluminescence images of the flame are taken for flame visualization. By utilizing the LIF technique, the present setup is capable of measuring near-wall OH* and also flame temperature with the OH 2-line method [6]. UV laser beam from the dye laser is condensed to thin laser sheet with a thickness of 0.5 mm, and introduced from the bottom of the combustor for excitation of the OH* radical.

3. EXPERIMENTAL RESULT

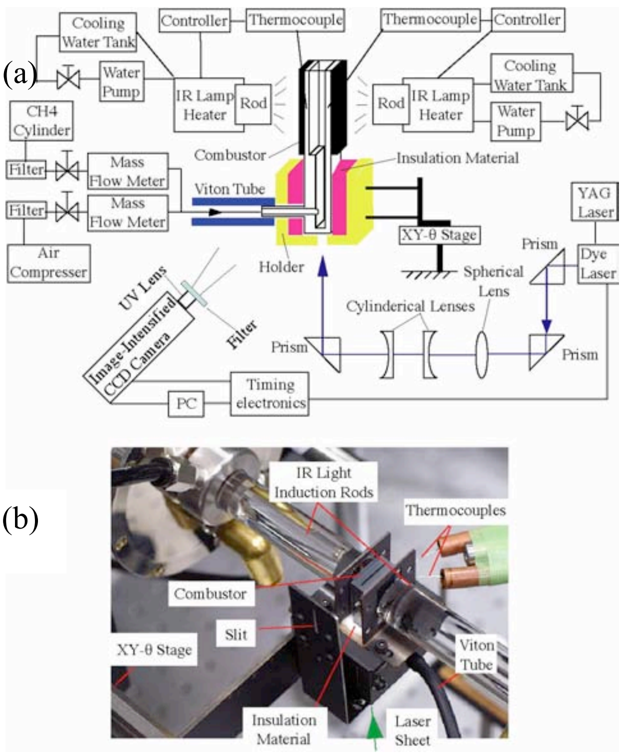

Fig. 2: Experimental setup. (a) Schematic, (b) Magnified view of the combustor.

Prior to the flame observation, outer surface temperature of the combustor sidewall is measured by a radiation thermometer with sensing wavelength of 5.14 μm. Figure 3 shows the temperature profiles along the centerline of the combustion channel. The temperature variation in the streamwise direction is within 200°C both for T_{TC}=800°C and 1000°C. When a flame exists inside the channel, local temperature near the flame increases by about 100°C. As shown in Fig. 4, the temperature difference of the outer surface in the wall normal direction is within 50°C.

Two flame patterns, steady flame and oscillating flame, have been observed in all three combustion channels. For the steady flame, as indicated by the temperature profile change in Fig. 3, the flame position moves closer to the exit with increasing the air flow rate. Figure 5 shows an oscillating flame in the 0.7-mm-thick combustion channel. For the oscillating flame, the flame cell keeps moving upstream from the exit periodically. The process can be explained as follows: the flame ignites at the combustor exit, and quenches when it goes upstream where the wall temperature is lower. The oscillating frequency and quenching position change with different wall temperature and flow rate (not shown).

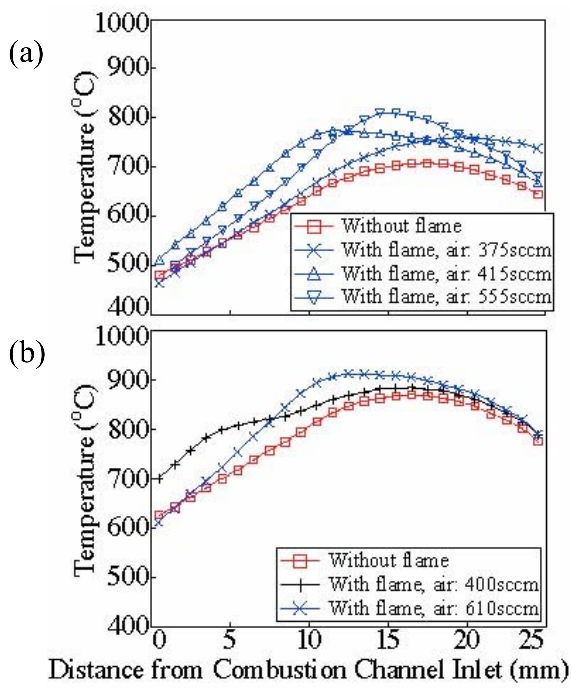

Fig. 3: Temperature profile along the centerline of the combustion channel at the sidewall outer surface. CH_4 flow rate is 45.6 sccm. (a) T_{TC}= 800°C; (b) T_{TC}=1000°C.

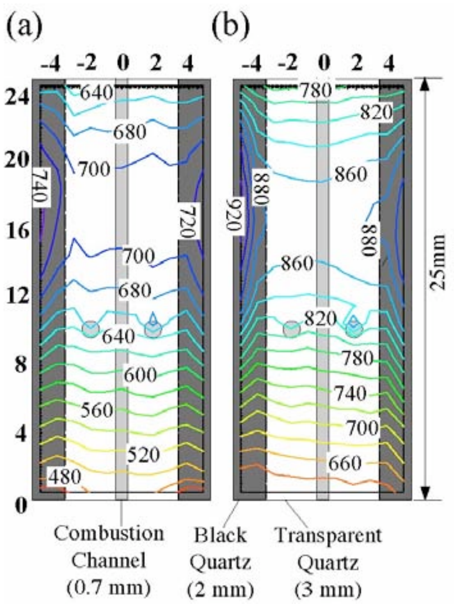

Fig. 4: Temperature contours at the outer surface of the sidewall. (a) T_{TC}=800°C; (b) T_{TC}=1000°C.

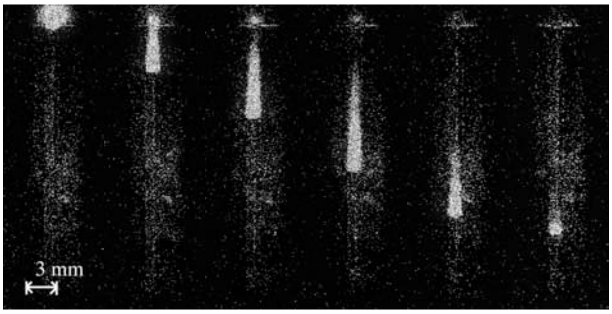

Fig. 5: OH chemiluminescence of oscillating flame in the 0.7-mm-thick combustion channel. Optical band-path filter at 307 nm is employed.*

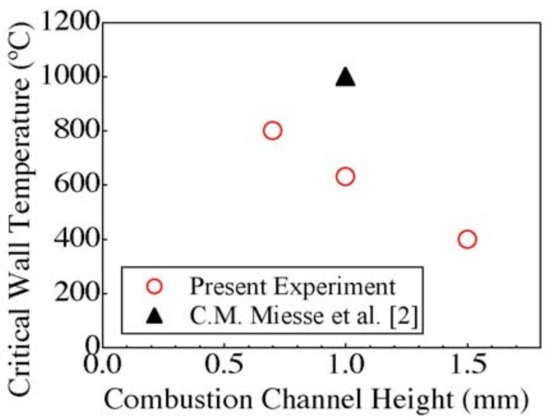

Fig. 6: Effect of the combustion channel height on the critical wall temperature.

As shown in Fig. 6, critical wall temperature for flame to exist becomes higher for thinner combustion channel, which means that more thermal input is necessary for thinner channels due to stronger wall effect. Miesse et al. [4] report that the quenching distance for high wall temperature (near 1000°C) strongly depends on the surface material and chemical quenching prevails, whereas the thermal quenching plays a dominant role at lower wall temperature. However, in the present result at 800°C, flame can still propagate in a 0.7-mm-thick quartz channel, which is smaller than the wall gap of 1 mm previously reported [4]. Since the quenching distance is still dependant on the wall temperature, one can expect that thermal quenching mechanism plays an important role even at high wall temperature.

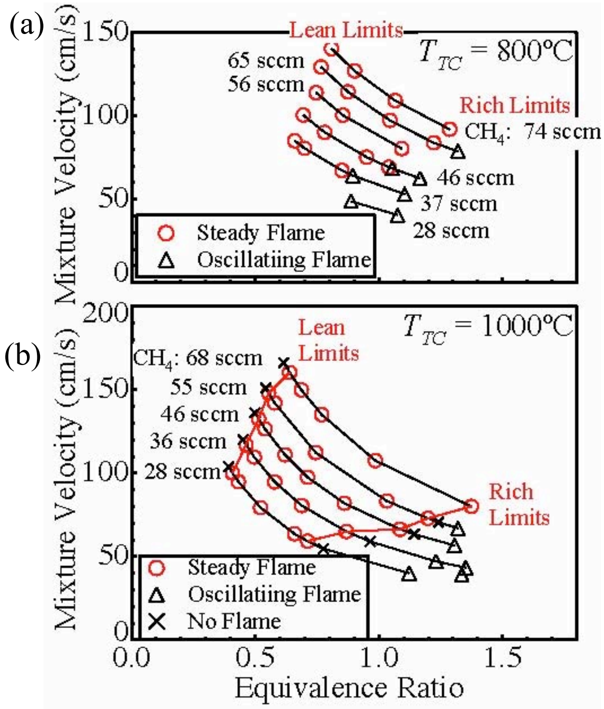

Fig. 7: Flammability limits in the 0.7-mm-thick combustion channel. (a) T_{TC} = 800°C, (b) T_{TC} = 1000°C.

Figure 7 shows the flammability limits in the 0.7-mm-thick channel for different wall temperatures. Compared with the steady flame, oscillating flame is in the higher equivalence ratio region. In this region, the CH_4/air mixture can not be ignited inside the combustion channel, so that flame propagates at the exit first, and then becomes oscillating. The flammability limits region becomes broader with increasing wall temperature. Compared with the data in a 2-mm-diameter tube combustor [3], the present combustor should have stronger wall effect due to the higher surface-to-volume ratio and narrower channel. However, the flame in the present combustor can be stabilized at much higher velocities. It is conjectured that the recirculation zone downstream the backward-facing step in the combustion channel stabilizes the flame. It is also noted that the range of the equivalence ratio within the flammability limit is narrower than the data in the long tube combustor [7].

Figure 8 shows the flammability limits in the 1.0-mm-thick channel. Compared with the 0.7-mm-thick channel, the 1.0-mm-thick channel has a broader flammability limits region for the wall temperature of 800°C, but the flammability region is only slightly enlarged for the higher wall temperature of 1000°C. This is probably because the wall effect on quenching for the thinner combustion channels becomes more severe at low wall temperature. The maximum CH_4 flow rate for steady flame is 92 sccm for the 1.0-mm-thick channel, while it is only 74 sccm for the 0.7-mm-thick channel. This is due to the blow-off, because the maximum flow rates correspond to almost the same bulk gas velocities.

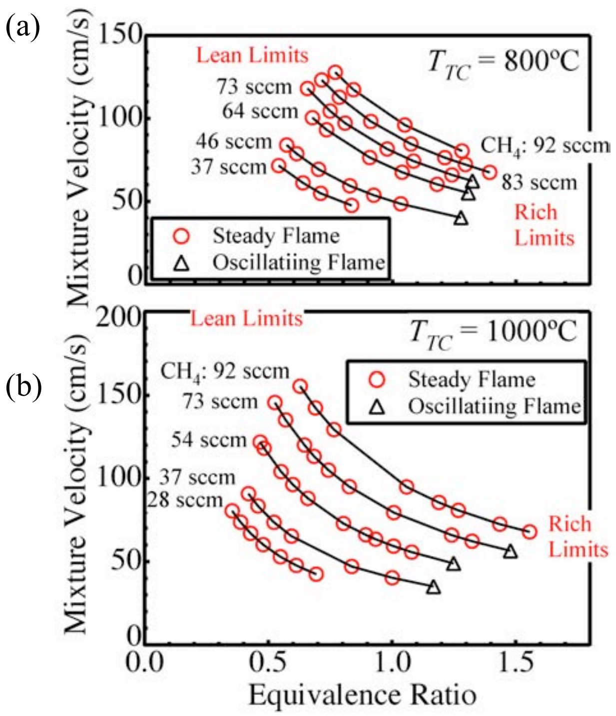

Fig. 8: Flammability limits in the 1.0-mm-thick channel. (a) T_{TC} = 800°C, (b) T_{TC} = 1000°C.

4. CONCLUSION

Micro quartz combustor that enables optical access has been developed for the investigation of quenching mechanisms in micro channels. Premixed CH4/air combustion is examined in the quartz combustion channels with the height of 0.7, 1.0 and 1.5 mm. The following conclusions are derived: (1) Quenching distance in the quartz channel is dependant on the wall temperature, and can be smaller than 0.7 mm for the wall temperature over 800°C. (2) Flammability limits region becomes narrower for thinner channel. (3) Flammability limits region becomes broader with increasing wall temperature, and the backward-facing step design in the present combustor helps stabilizing the flame for high mixture velocity.

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