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ULTRA-THIN QUARTZ COMBUSTORS FOR TPV POWER GENERATION

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Abstract: Premixed CH_4/air flame in planar quartz combustors with channel height of 0.7/1.0/1.5 mm have been investigated for micro thermophotovoltaic (TPV) application. Quenching distance in parallel quartz plates with/without Cr-coating has been experimentally studied. The quenching distance decreases as the wall temperature is increased, and slightly changes for different wall surfaces. OH* planer laser-induced fluorescence (PLIF) images of micro flame shows a concave shape of the flame front. It is also found that the flame temperature depends on the wall temperature.

Keywords: Quenching distance, Micro combustor, Wall/flame temperature, PLIF

1. INTRODUCTION

One of the promising concepts for portable power generation is the TPV system that produces electrical power from the intense radiation released by hydrocarbon combustion. Figure. 1 shows the concept of micro TPV system, which consists of a gas-phase combustor [1] with imbedded heat exchanger for pre-heating, a selective emitter for radiation modulation [2], an ejector for fuel-air supply [3], and a PV cell for photovoltaic conversion. As for the radiation source, high-temperature gas-phase combustor is preferred, because radiation energy in the shorter wavelength range is increased with the temperature. However, gas-phase combustion is difficult to maintain in micro scale due to significant thermal and chemical quenching near the wall. Extensive research efforts have been made on the 'Swiss-roll' combustors, which establish combustion by heat recirculation or external heating [4]. Recently, Miesse et al. [5] claim that inert materials such as quartz, alumina and cordierite are effective against radical quenching near the wall.

In the present study, planar quartz combustors with channel height of 0.7/1.0/1.5 mm have been developed. Premixed CH4/air flame is established in the combustion chamber by precise control of heat input to the wall. In practical systems, the heat losses should be reduced by vacuum insulation and heat recirculation instead of being compensated by external heat input. Nevertheless, the controllability of heat input here enables the discussion of wall thermal effects quantitatively. The design of the combustor and the details of flammability limits and flame oscillation have been discussed elsewhere [1]. The primary focus of the present paper is on the quenching distance and characteristics of steady flame in micro combustors.

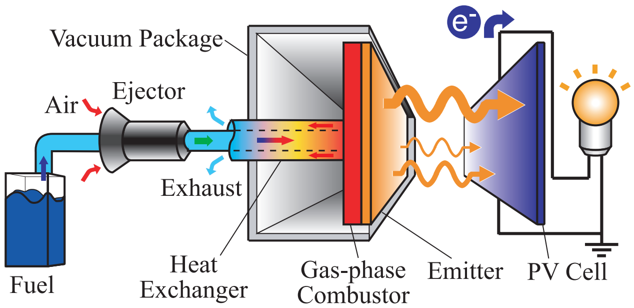

Fig. 1: Schematic of micro TPV system concept.

2. QUENCHING DISTANCE IN PARALLEL PLATES

Quenching distance is experimentally investigated for the determination of the channel height of the micro combustor. The quenching distance here is defined as the minimum gap between two parallel plates that allows flame to propagate through. Note that the quenching distance may quantitatively differ in different experimental configurations, but the measured value should be comparable in order.

Figures 2 and 3 shows schematic and photos of the experimental setup, and the sample plates are shown in Fig. 4. Two sample plates are hold parallel to each other, and one of them is fixed to a XYZ stage for adjusting the gap manually. The base plate is made of polished synthetic quartz, and is fusion-bonded with black quartz (Nb-doped quartz) plates for absorption of IR light as the heating source. Two R-type thermocouples (ϕ =0.5 mm) are plugged into 1-mm-diameter holes opened in the transparent quartz layer of the top and bottom walls. Wall temperature measured with the thermocouple T_{TC} is regulated by adjusting the lamp power. Stainless steel tube with inner diameter of 2 mm and ceramic tube with inner diameter of 0.8 mm are employed as the burner to introduce flame into the gap. The burner is fixed to a

XYZ stage to adjust its position to the plates. CH_4 fuel is supplied from a gas cylinder, and premixed with air that is introduced from a compressor. The CH_4 and air flow rates are separately measured and regulated by two sets of flow meters and valves. At first, flame is initialized at the top of the gap as shown in Fig. 3. While the tube burner is moving backwards, the flame is likely to propagate upstream. A high-speed ICCD camera (FASTCAM, Photron) is placed in the sideway to capture the propagation of the flame up to 2000 frames per second. OH* chemiluminescence images are taken for flame visualization with an f =105mm UV Nikkor lens and an optical band-path filter at 307±10 nm.

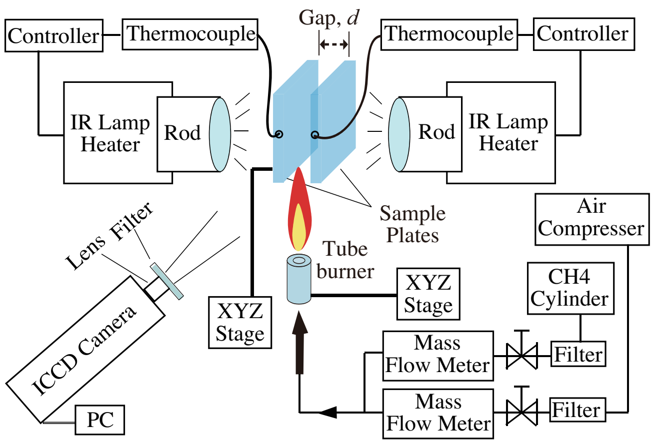

Fig. 2: Schematic of experimental setup for quenching distance measurement.

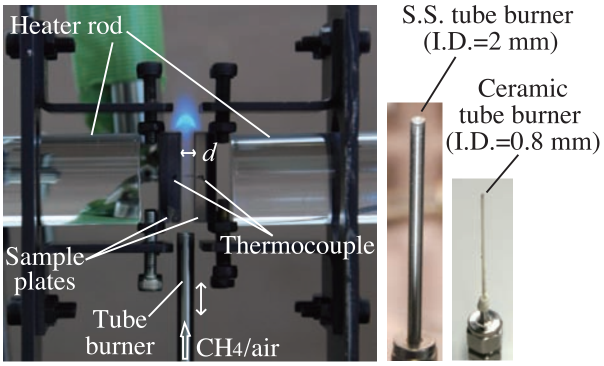

Fig. 3 Magnified view of the experimental setup for quenching distance measurement and tube burners.

Quenching distance measurements are made with one pair of quartz plates and one pair of quartz plates with 50 nm-thick Cr coating. Chromium is metallic, though it is not generally considered active in hydrocarbon combustion. Quartz is more inert, and is claimed to be able to suppress the radical adsorption and trapping at the surface during combustion [5]. The 2 pairs of plates only differ in surface coating so that the plates only quench the flame differently in the chemical aspects. Tube burners having inner diameter of 0.8 mm and 2 mm are alternatively used, and the quenching distance results are consistent for different burners. Flow rates are also checked to be not influential in the results.

Figure 5 shows the quenching distance results. When heat loss is compensated as the wall temperature is increased, the quenching distance for both quartz and Cr becomes smaller. Compared with Cr, quartz has slightly smaller quenching distance. These results show that unlike the previous report [5], the thermal quenching is still important for high wall temperatures. But, the chemical effect does exist, and an inert surface is preferable over the metallic one for the construction of micro combustors.

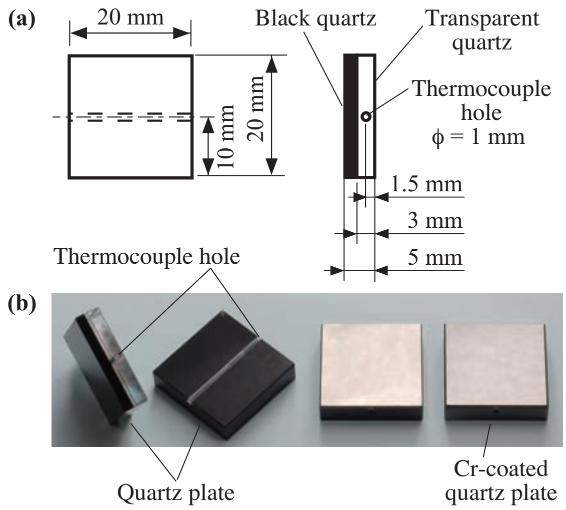

Fig. 4 (a) Schematic and (b) photos of the sample plates.

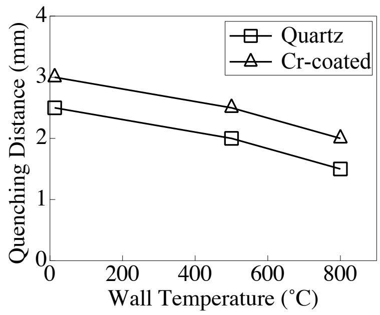

Fig. 5 Quenching distance between quartz plates with/without Cr coating.

3. MICRO COMBUSTORS AND EXPERIMENTAL RESULTS SETUP

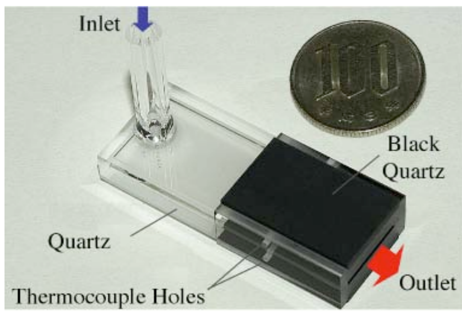

Fig. 6: Micro quartz combustor.

3.1 Quenching Distance in Micro Combustors

Based on the quenching distance results, three quartz combustors are designed with combustion channel heights, *d*, of 0.7 mm, 1.0 mm and 1.5 mm, respectively. As shown in Fig. 6, the combustors are fabricated in a similar manner of the quartz plates with inner wall of transparent quartz and outer wall of black quartz, and the details of the combustor and experimental setup for combustion can be found in [1]. The combustor is held vertically with its exit facing upwards, and the streamwise motion of flame is captured by the high-speed ICCD camera.

When the wall temperature is raised beyond a critical value, flame propagates into the combustion channel. Two flame patterns, steady flame and oscillating flame, have been observed in all three combustors. Chemiluminescence images of the flame and detailed discussion of flame oscillation can be found in [1]. Figure 7 shows the flammability limits in the 0.7-mm-thick and 1.0-mm-thick channels for different wall temperatures. Compared with the 0.7-mm-thick channel, the 1.0-mm-thick channel has a broader flammability limits region. The flammability limits region becomes narrower with decreasing wall temperature, and vanishes at a critical wall temperature. The critical wall temperature for flame to exist in the d=1.5, 1.0 and 0.7 mm combustors is around 400°C, 650°C and 800°C, respectively. The quenching distance in the combustor is smaller than that in the parallel plates because mass and heat can be transferred out from the sideway in the case of parallel plates. On the other hand, these losses are confined by the sidewalls in the combustor.

3.2 Micro Flame Structure by OH-PLIF

Since the chemiluminescence of the flame is integrated in the plane-normal direction for direct chemiluminescence images. The void of 3-D information may lead to misunderstanding of the real shape of the flame. On the other hand, by using OH-PLIF it is possible to 'cut' and display the flame slice-by-slice, so that the 3-D structure can be revealed.

Figure 8 shows the setup for the OH-PLIF experiment. The combustor is held horizontally with its exit facing to the camera. The ICCD camera (Flamestar2, La Vision) is synchronized with a dye laser (Lambda Physik) for the detection of the OH fluorescence signal at the $Q_1(8)$ transition. Thin laser sheet with a thickness of 0.3 mm is shaped by spherical and cylindrical lenses, and introduced perpendicularly to the combustor sidewall by a prism mirror. A slit is placed between the prism and the combustor to cut the laser sheet into approximate 1.5 mm in width, so that the cross-sectional plane of combustion channel is illuminated without inducing serious reflection at the inner sidewall. By moving the prism with a traveling stage, the laser sheet is fed to illuminate a slice of the flame at a different streamwise position. In order to reconstruct the 3-D flame structure, a series of slice OH-PLIF images are then taken by scanning the laser sheet continuously in the streamwise direction.

Figure 9 shows continuous scanning OH-PLIF images of a steady flame in the *d* = 1.5 mm combustor. The streamwise distance between two adjacent slices is 1 mm. It is obvious from these images that the flame is concave to the inlet side. The image taken upstream shows a small spot with high OH-PLIF intensity, which represents the valley of the flame. Going

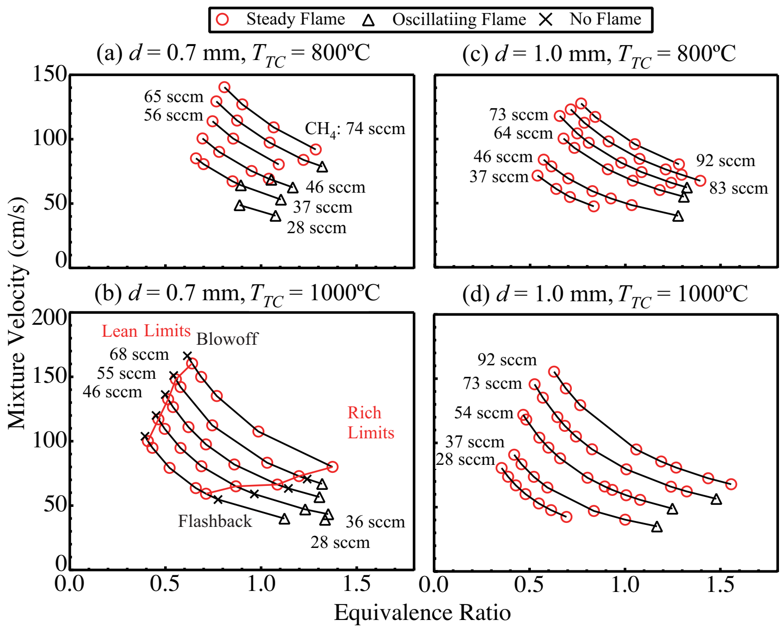

Fig. 7: Flammability limits in combustors having channel heights of 0.7 and 1.0 mm.

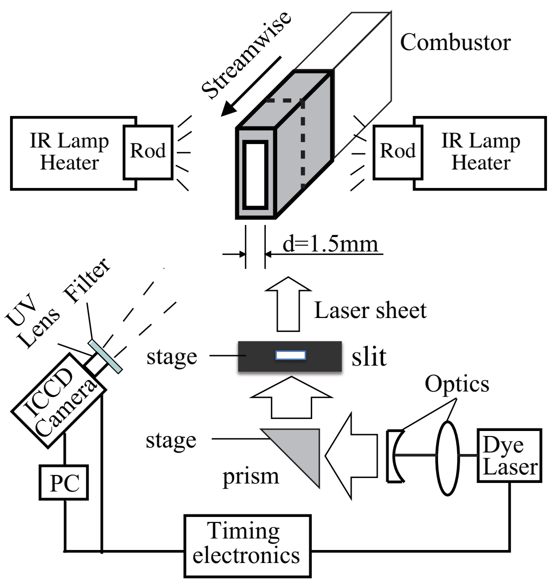

Fig. 8: Schematic of experimental setup for OH-PLIF.

downstream, the spot expands and separates into two spots, and the two spots separate farther and farther, and almost vanish about 6 mm downstream. The deformation of flame front is possibly caused by higher flame velocity in the combustor centerline as a consequence of the non-uniform wall-temperature distribution. Since the IR light induction rod of the lamp heater is circular and 20 mm in diameter, it imposes a radial temperature distribution to the combustor wall.

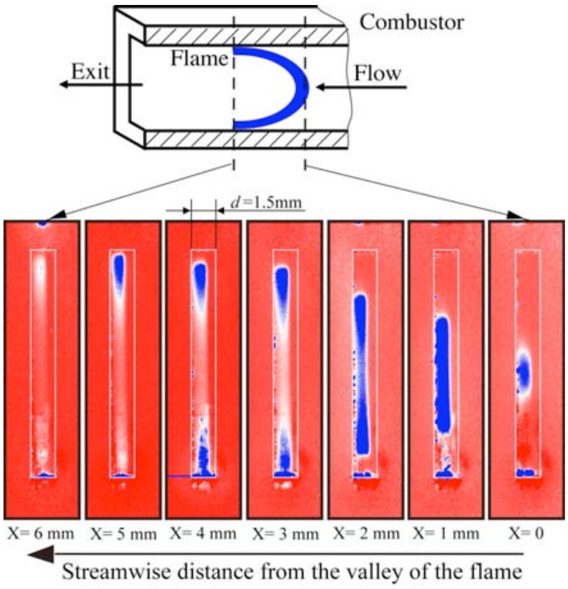

Fig. 9: OH-PLIF images of steady flame.

3.3 Flame Temperature

Inner wall surface temperature is measured by a radiation thermometer through four 2-mm-diameter circular windows opened perpendicular to the top wall of the combustor [1]. As shown in Fig. 10, the inner wall surface temperature for T_{TC}=800°C has a peak at 15 mm downstream the inlet, and becomes lower away from the peak position.

OH 2-line method [6] is employed to measure the flame temperature, and the result is compared with the gas temperature measured by SiO_2-coated B-type thermocouples (ϕ =0.1 mm) at the centreline of the combustion channel. For the OH 2-line method, OH $P_1(7)$ transition at 285.005 nm and $Q_2(11)$ transition at 285.073 are adopted, and the OH-PLIF intensity is averaged from 50 images each. The existence of flame leads to a steep rise of the measured gas temperature, with the peak corresponding to the flame temperature. As shown in Fig. 10, the flame temperature increases about 200°C when wall temperature is elevated from 500°C to 800°C. The flame temperature is dependent on the wall temperature because of the heat convection from the upstream wall to the un-burnt gas. The flame temperature measured by the thermocouple is approximately 100°C lower than that by the OH 2-line method due to the radiation loss from the thermocouple. Note that both the two flame temperatures by thermocouple and OH 2-line method are much lower than the theoretic adiabatic flame value of approximately 1800°C, which is mainly due to the serious heat loss from the flame zone to adjacent walls.

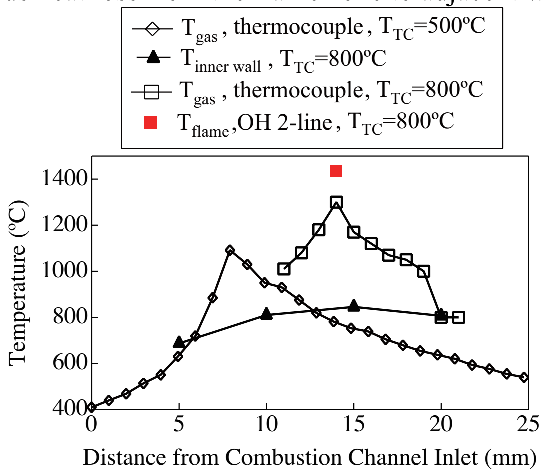

Fig. 10: Gas/flame temperature at the combustion channel centre-line.

4. CONCLUSIONS

Micro quartz combustors having channel heights of 0.7/1.0/1.5 mm have been developed for TPV applications. Investigations of the quenching distance in parallel plates and micro combustors show that both the wall thermal effect and chemical effect have contributions in the quenching of flame. OH-PLIF images of micro flame shows a concave-shape flame front, which is the result of the non-uniformity of wall-temperature distribution. In micro combustors, flame temperature becomes strongly affected by the wall temperature.

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