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On Flame-Wall Thermal-Coupling in Micro Combustors

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Abstract: This paper presents the 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. Discussion has been made on the effect of thermal coupling between flame and wall, and its contributions to the process of flame oscillation. According to well-resolved chemiluminescence images of the flame taken by the high-speed ICCD camera, flame oscillation is interpreted as a periodic process of ignition at the exit and quenching by heat loss to the wall.

Hydrocarbon-fueled micro combustor is of great interest in portable power generation applications for high energy density. However, gas-phase combustion becomes problematic in micro combustors with a characteristic length comparable to the flame thickness. The effects of heat loss and radical destruction from the combustor wall become significant with the increase of surface-to-volume ratio, and eventually the flame is likely to be quenched. Extensive research efforts have been made recently on excessive enthalpy combustors such as the 'Swiss-roll' combustor which establish combustion with heat recirculation (Maruta et al., 2004). On the other hand, the wall chemical effect has been investigated by Miesse et al. (2004) and Kim et al. (2006) in their quenching distance measurements. Inert materials such as quartz, alumina and cordierite are found effective against radical quenching near the wall.

In the present study, experimental observation and analysis of flame propagation and quenching have been made in ultra-thin planner quartz channels with precise wall-temperature control. The effect of flame-wall thermal-coupling on flame oscillation is discussed.

The micro combustors and main experimental setup are shown in Fig. 1 (Fan et al., 2007). The inner wall of the combustion channel is made of polished synthetic quartz for optical access in the experiment as well as the suppression of the radical adsorption and trapping at the surface during combustion. The quartz combustors have combustion channel heights d of 0.7 mm, 1.0 mm and 1.5 mm, which are smaller than conventional quenching distance for hydrocarbons. The top and bottom sides of the channel are fusion-bonded with black quartz (Nb-doped quartz) plates for absorption of IR light as heating source. Two R-type thermocouples (ϕ =0.5 mm) are plugged in 1-mm-diameter holes opened in the transparent quartz layer of the top and bottom walls. Wall temperature measured with the thermo couple T_{TC} is regulated by adjusting the lamp power. The combustor is held vertically, and a high-speed ICCD camera (FASTCAM, Photron) is placed in the sideway to capture the streamwise motion of the flame. OH* chemiluminescence images are taken for flame visualization up to 2000 frames per second.

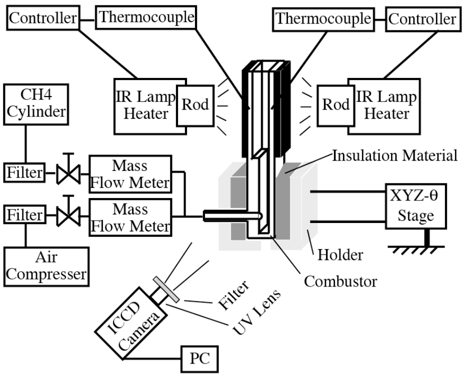

Fig. 1. Schematic of experimental setup.

Figure 2 shows the gas temperature measured at the centreline of the combustion channel by B-type thermocouples (ϕ=0.1 mm). The temperature of un-burnt gas is elevated by the heating from the upstream wall, and the flame temperature, as a consequence, also becomes dependent on the wall temperature. Note that the flame temperature measured here is much lower than the theoretic adiabatic flame value of approximately 1800°C, which is due to the heat loss from the flame zone to the adjacent walls.

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 combustion channels. Flammability limits and steady flame are discussed in Fan et al. (2007), and the oscillating flame is presented here. One flame oscillation process that is clearly tracked by time-resolved OH* images (1 ms interval time) is shown in Fig. 3. Flame ignites at the combustor exit at first. This gives the flame an initial heat input. When the exit flame cell gathers certain amount of heat, it grows, expands, and propagates into the combustor. However, when flame is travelling upstream in the channel, the flame continuously losses heat to the wall. The flame quenches upstream where it cannot pace further. The fresh un-burnt mixture then recharges to the exit for another oscillating cycle. According to the observation, one may divide one oscillation cycle into three main stages, i.e. the ignition (initialization) stage, the propagation stage, and the recharge stage. Then the oscillation frequency can be expressed as

$$\frac{1}{frequency} = ignition\_time + \frac{amplitude}{propagating\_velocity} + \frac{amplitude}{mixture\_velocity}. \quad (1)$$

The oscillation frequency under most experimental conditions is in the range of 30-500 Hz as show in Fig. 4. When keeping the methane flow rate, the frequency is found to decrease with increasing the mixture velocity. This is because the oscillation amplitude increases with the mixture velocity.

Figure 5 shows the transient propagating velocity of an oscillating flame. The transient propagating velocity varies during the propagation stage of one oscillation process, and the propagation becomes slower as the flame gets closer to the quenching position. Since the laminar flame velocity is decreased with the flame temperature, the ‘slow-down’ phenomenon supports the hypothesis of gradual heat loss from the flame to the wall.

The above discussion comes to the fact that combustor wall and flame in micro scale affect each other in a coupled manner. The temperature of un-burnt gas is significantly affected by the pre-heating from the upstream wall, so that the flame temperature also becomes dependent on the wall temperature. On the other hand, the wall temperature is still lower than the flame temperature, and thus heat is always lost from the flame to the adjacent wall. However, the flame-wall thermal-coupling should be treated somewhat differently in the analysis of steady and oscillating flames. For the steady flame, the energy conservation principle can be applied; there should be considerable local wall temperature raise due to heat loss from the flame to the wall. Thus, the wall temperature becomes less uniform. But for the oscillating flame, energy conservation is not hold in the same way because time scale of the flame passage is faster than thermal response of the combustor wall.

Premixed CH_4/Air flame propagation and quenching in ultra-thin quartz channels are investigated. Wall temperature shows strong effect on the flame temperature and velocity. Flame and wall influence each other in a coupled manner. Flame oscillation is a consequence of the thermal-coupling, and is interpreted as a periodic process of ignition at the exit and quenching by heat loss to the wall.

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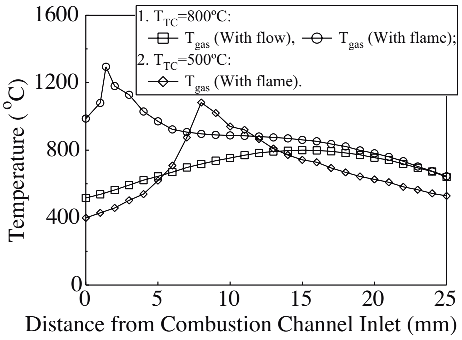

Fig. 2. Gas temperature at the channel centre-line.

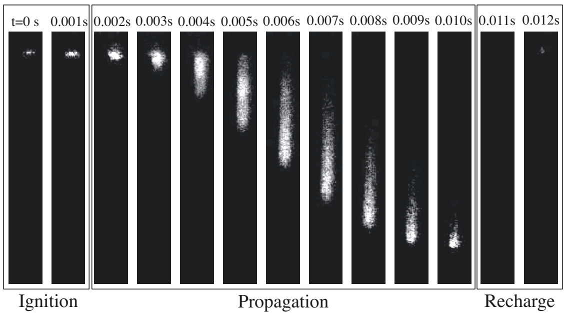

Fig. 3. OH* chemiluminescence of oscillating flame.

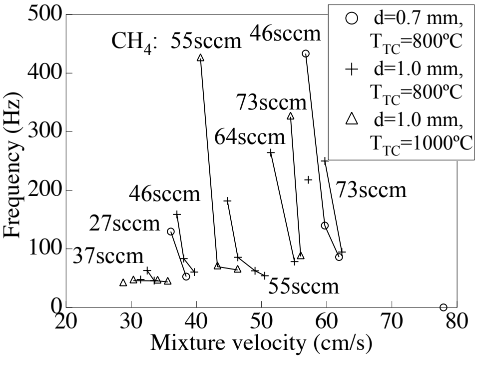

Fig. 4. Oscillation frequency.

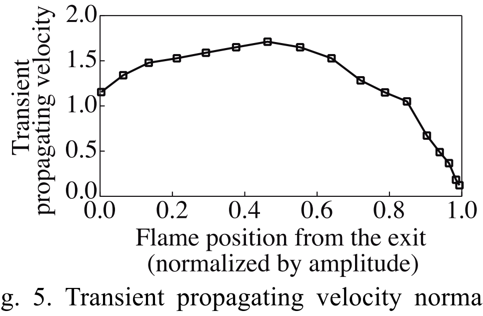

Fig. 5. Transient propagating velocity normalized by the mean propagating velocity.