

# Extinction characteristics of premixed flame in heated microchannel

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## 1. Introduction

Understanding the combustion characteristics in a microchannel is important for the development of micro scale combustors. In general, with decrease of combustor size, the effect of heat loss increases so much due to large surface-to-volume ratio of small combustor. To overcome flame quenching and instabilities induced by heat loss, the utilization of heat recirculation burners such as Swiss-roll combustors [1] is an effective method. In order to examine the general characteristics of combustion with heat recirculation, Maruta et al. [2] have applied external heating to a cylindrical quartz glass tube and investigated behavior of flame that was established in the tube with temperature gradient. They showed that flame could be stabilized in a meso-scale channel whose inner diameter was smaller than the conventional quenching diameter. However, much smaller scales prevent the experimental approach such as flame observation and measurement. One possible solution for those difficulties is using of the meso-scale channel under low pressure conditions because the flame becomes thicker with decrease of pressure. Kim et al. [3] conducted experiments in a large tube at low pressure, where the flame becomes similar to that in a narrow tube at normal pressure. Their results indicated that the scale effect can be investigated since combustion characteristics are maintained even under the low pressure conditions. Therefore combustion in extremely small tube at normal pressure can be simulated experimentally by using meso-scale channel under low pressure conditions. In this study, the effects of pressure (0.05-0.2 atm), flow velocities, and mixture compositions on extinction limit were investigated with externally heated meso-scale channels.

## 2. Experimental setup and methods

Cylindrical quartz glass tube, whose inner diameter and length are 2.0 mm and 300 mm was employed as shown in Fig. 1. Well premixed methane-air mixtures were supplied to the channel by mass flow meters. Pressure in the channel was controlled by vacuum pump and bypass bulb and monitored with a Pirani gauge. An image-intensified CCD camera with CH filter was used to observe flames. The channel was heated up to 1350K by a hydrogen-air flat flame burner. The flame in the channel was stabilized in the region with positive temperature gradient, which resembles heat recirculation. After self-ignition at 1atm, pressure and flow rate were adjusted.

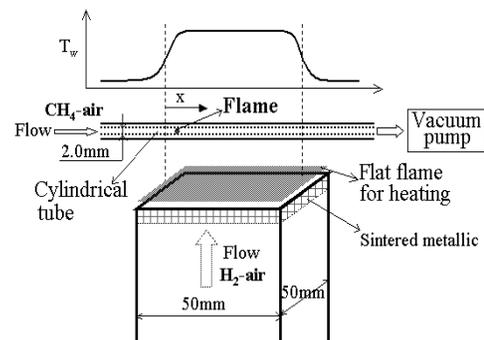


Fig. 1 Schematic of experimental apparatus and temperature distribution in the tube

### 3. Experimental results

Figure 2 shows measured flammable region. Each symbol indicates the upper limit of flow velocity at each equivalence ratio. In this experiment, the flame blows off at the location of maximum wall temperature. The flame extinction was identified by images of ICCD camera. However it is difficult to observe the flame quenching at fuel lean and rich conditions because of very low luminosities. Flammable regions become narrower with decrease of pressure. In addition, each flammable region at rich side is narrower compared with very lean conditions and maximum extinction limits appear around  $eq.=0.5-0.9$ . Therefore, it shows asymmetric tendency to the stoichiometric ratio, while conventional flammable region is symmetric in general [3]. In addition, the maximum extinction limits for each pressure shifts to stoichiometric ratio with increasing pressure.

Figure 3 shows flame images at normal and low pressures. The flame at low pressure has low luminosity and is thicker than flame at normal pressure. Figure 4 shows estimated flame thicknesses at extinction limit for each pressure. The flame thickness was estimated as follows [4]

$$\delta = \frac{k}{C_p \rho_u^o V_o} \quad (1)$$

where,  $k$  and  $C_p$  are thermal conductivity and specific heat evaluated from the products at mean temperature and  $V_o$  is flow velocity at the extinction limits in Fig. 2. The mean temperature was estimated as the simple mean of the adiabatic flame temperature at low pressure condition and the maximum wall temperature (1300K). Species concentrations at the mean temperature and the adiabatic flame temperature were calculated based on the chemical equilibrium conditions. Figure 4 shows that the flame thicknesses at low pressures are several times larger than that of methane-air flame at normal pressure ( $\sim 0.12\text{mm}$ ). Especially, at 0.05atm, the flame thicknesses are almost the same as channel diameter. Therefore the combustion in extremely small tube could have been simulated.

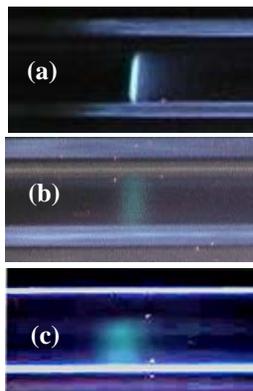


Fig. 3 Flame images ( (a)  $p=1.0\text{atm}$ ,  $eq.=1.2$ , (b)  $p=0.6\text{atm}$ ,  $eq.=1.2$ , (c)  $p=0.4\text{atm}$ ,  $eq.=1.2$  )

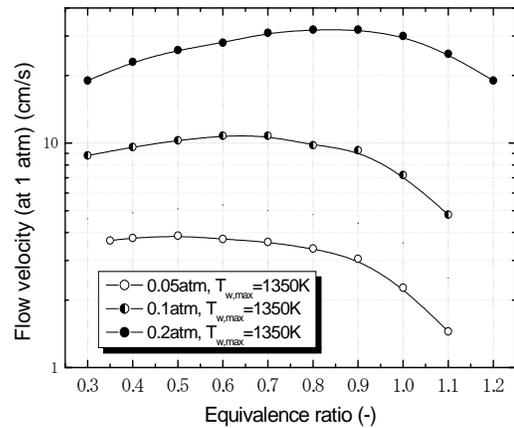


Fig. 2 Measured flammable region

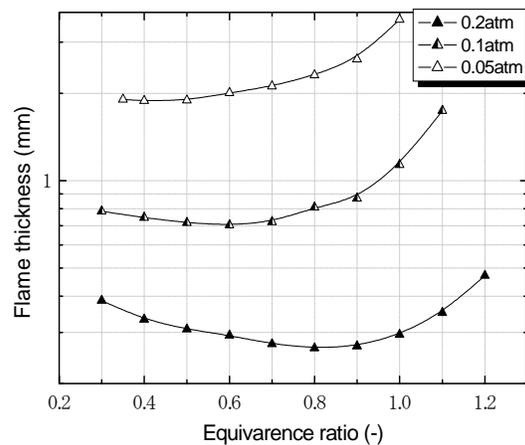


Fig. 4 Flame thicknesses

Figure 5 shows the characteristic residence times at the extinction limits which were estimated from  $\tau_{res} = \delta/V_g$ , where  $\delta$  is flame thickness in Fig. 4 and  $V_g$  is defined as  $V_g = \rho_u V^0 / \rho_b$ .  $\rho_u$  and  $\rho_b$  are densities for unburned and burned gases which were estimated by using chemical equilibrium calculation. Because Damkohler number ( $D = \tau_{res}/\tau_{ch}$ ) at extinction limits can be regarded as almost constant at each pressure, we can estimate the tendency of characteristic chemical time from Figure 5, where minimum characteristic residence time shifts to fuel lean side. It is quite different from the conventional chemical time, which attains minimum close to stoichiometric ratio. One possible reason of this unusual tendency is using of the external heating.

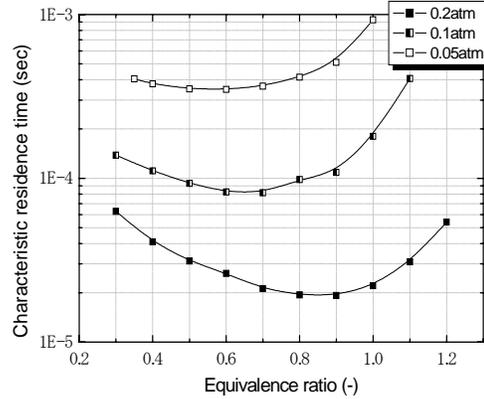


Fig. 5 Characteristic residence time

Changing equivalence ratio changes not only fuel concentration but also flame temperature simultaneously [1]. In general, the maximum flame speed appears close to the stoichiometric ratio since flame temperature becomes highest. Therefore flame stability depends on its own temperature for the case without external heating generally. However, in this study, since the wall temperature of a part of the channel is maintained at very high by the external heating, the effect of heat loss is not significant. Thus, the effect of fuel concentration change may have larger influence on the flammable region than that of flame temperature change.

#### 4. Computational methods and results

To further examine the experimental results, 1D computations with detailed chemistry were conducted. A PREMIX-based code with a modification in energy equation [2] and C-1 chemistry were used. The modified equation is as follows:

$$\dot{M} \frac{dT}{dx} - \frac{1}{c_p} \frac{d}{dx} \left( \lambda A \frac{dT}{dx} \right) + \frac{A}{c_p} \sum_{k=1}^K \rho Y_k V_k c_{pk} \frac{dT}{dx} + \frac{A}{c_p} \sum_{k=1}^K \dot{\omega}_k h_k W_k - \frac{A}{c_p} \frac{4\lambda Nu}{d^2} (T_w - T) = 0 \quad (2)$$

Convective heat transfer between the wall and gas is considered. Nusselt number of the inner wall surface was assumed to be constant ( $Nu = 4$ ).  $T_w$  is the wall temperature and the profile in the computation was the same as that of the experiment. The maximum wall temperature is 1300 K.

Figure 6 shows computed flammable regions. Flame position was decided by the peak of CH mole fraction. The definition of blow off is that the flame crosses over the location where the wall temperature reaches its maximum. The results show fair agreements with measured flammable regions. Flammable region is narrower with decrease of pressure and there are maximum extinction limits at fuel lean side. It was found that the maximum for each pressure shifted to stoichiometric ratio with increasing pressure.

Figure 7 shows the variation of the computed flame temperature ( $T_g$ ) in flammable region and adiabatic flame temperature ( $T_{adi}$ ) for methane-air. The flame temperature is defined as the gas peak temperature. Results show that the computed flame temperature for each pressure becomes maximum close to the stoichiometric condition as well as the adiabatic flame temperature. Furthermore, there is small change in flame temperature with variation of equivalence ratio, since the flame temperature is dominated by wall temperature. Therefore, the

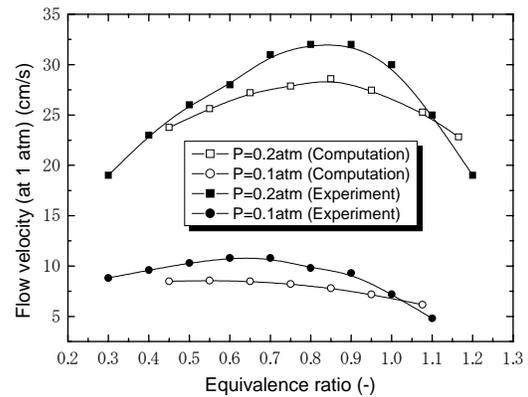


Fig. 6 Computed flammable region

profile of the flame temperature becomes flatter than that of adiabatic flame. It indicates that the effect of flame temperature on the present flammable region is smaller than that of normal flame case. In addition, the temperature change with equivalence ratio becomes larger with increase of pressure as shown in Fig. 7. This means that the flame temperature has a large effect on flammable region as the pressure approaches to atmospheric pressure. Therefore the maximum extinction limits for each pressure shift to stoichiometric ratio with increase of pressure in the result of measured and computed flammable regions.

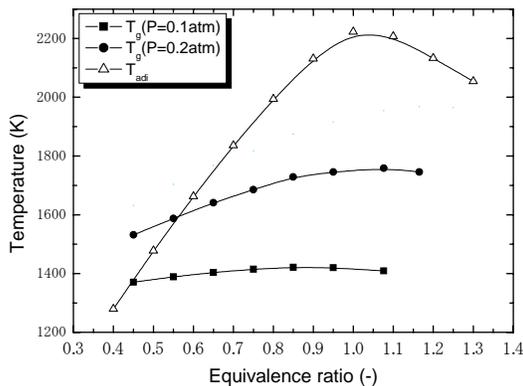


Fig. 7 Flame temperature

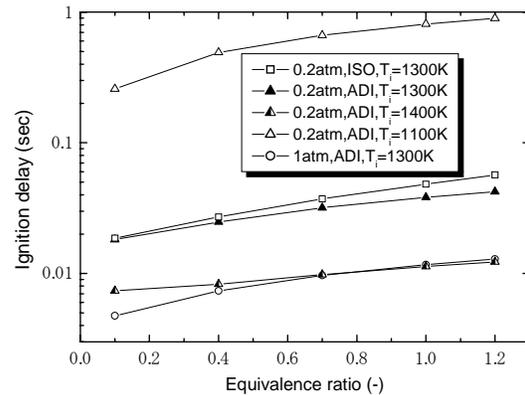


Fig. 8 Ignition delay

To investigate the effect of concentration change on the flammable region for the condition with external heating, the ignition delay times were calculated by the nondimensional and unsteady computations using an AURORA code and GRI-mech 3.0. Both adiabatic and isothermal cases were considered in the calculations. The initial temperature was equivalent to the maximum wall temperature in the experiment. The definition of ignition delay is the time from the start of heating to the peak of CH mole fraction. Figure 8 shows variations of the ignition delays for each condition. The ignition delay time becomes shorter monotonously with decrease of equivalence ratio regardless of the initial temperature, reaction condition and pressure. It is probably related to the tendency of the extinction limits whose maximum is located at lean side, because characteristic chemical time is shorter at lean side.

## 6. Conclusions

Combustion in small tube with temperature gradient under low pressure condition was investigated experimentally and numerically.

1. Measured flammable region became narrower with decrease of pressure and its maximum located at fuel lean side. In addition, flame thickness at low pressure became several times larger than flame at normal pressure.
2. Computed flammable region also became maximum at fuel lean side, which agreed with experiments.
3. It was found that the effect of the flame temperature variation with equivalence ratio on flammable region is not significant but that of reaction characteristic time is more important.
4. Maximum extinction limits located at fuel lean side in measured and computed flammable regions are supported to be due to the shorter characteristic chemical time at lean side.

## References

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