Relationship between Transient Characteristics of Burning Velocity Just After Ignition and Quenching Distance

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1 Introduction

The quenching distance is one of the key parameters showing the ignitability of the combustible premixture. It is especially important from the viewpoint of prevention of fire and explosion accidents and ensuring safety. So, much extensive research has been conducted and many characteristics of the quenching distance have been also revealed. For example, the measurement standards for quenching distance is established [1,2], and also found that the quenching distance is closely related to the burning velocity [3,4]. On the other hand, there are only some studies on the quenching distance of flammable mixture in flowing. The authors have also conducted a series of experimental research to develop the prediction model of the quenching distance in a flow of flammable mixture, and we have found that it could be predicted by the function of quenching distance in the quiescent flammable mixture and flow velocity. However, since the quenching distance in the quiescent premixture has not seemed yet always been predictable with good accuracy over the entire flammable range, it leads to insufficient accuracy of the prediction of the quenching distance in the flowing premixture. Therefore, we deeply investigated the characteristics of quenching distance in the quiescent premixture, especially focusing on changing the burning velocity with time just after the ignition.

2 Experimental Method

2.1 Quenching distance measurement

In this experiment, a loop-shaped combustion chamber shown in Fig.1 was used. The designated volume of fuel and oxidizer was introduced into this chamber using a syringe. A DC axial flow fan (40 mm square, maximum voltage of 12V) was installed in the vessel, and a homogeneous fuel-air mixture was generated by stirring with this fan. A pair of electrodes (Fig.2) which was made of a 2 mm of stainless rod with a 20 mm diameter of flange made by a quartz glass was installed in the chamber. The gap of electrodes can be arbitrarily changed with an accuracy of 0.01 mm using a dial gauge. Ignition experiments were conducted five times per a combination condition of gap length, equivalence ratio, and the variety of premixture. The maximum value among the gap of the electrode that no ignition was observed was determined as the quenching distance (hereinafter called d_{q2}). In this experiment, premixtures of methane/air and propane/air were used. The equivalence ratio (ϕ) ranged from 0.55 to 1.24 for the methane/air mixture and from 0.64 to 2.03 for the propane/air mixture.

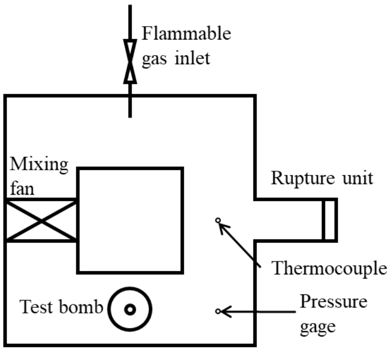


Fig.1 Schematic of the loop-shaped combustion chamber

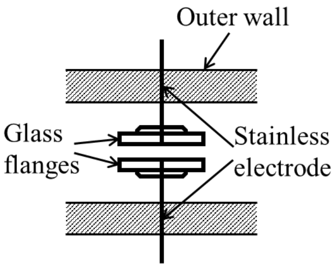


Fig.2 Schematic of electrodes

2.2 Combustion behavior analysis immediately after ignition

To analyze the transient behavior of the burning velocity in the early stage after ignition, we used the experimental results obtained by the laser-induced spark ignition method conducted in our laboratory [5]. The visible ignition behavior was taken by a high-speed camera with 50,000 fps. The pulse energy in which the ignition probability was 50%, which corresponds to the minimum ignition energy defined in the paper [5], was shot. The equivalence ratio (ϕ) was set in the range from 0.50 to 5.00. Since the shape of the flame kernel generated by the laser-induced spark ignition was vertically elliptical as shown in Fig.3, we paid attention to the vertical flame kernel diameter l_y because it seemed that there is little influence of flow to the propagation behavior of the flame kernel.

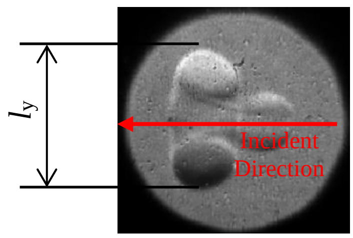


Fig.3 Shape of flame kernel just after ignition by laser induced spark

3 Results and Discussion

3.1 Comparison of experimental data of d_{q2} with prediction model

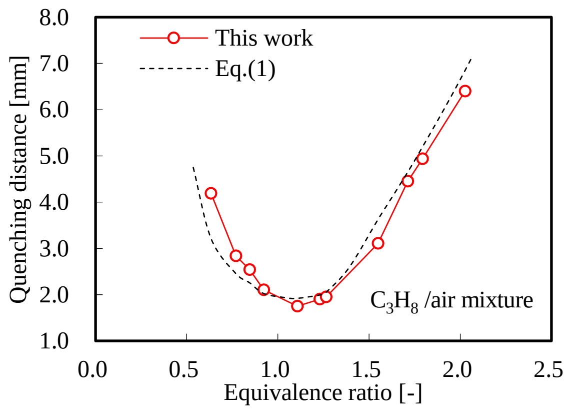
As shown in our previous report [6], the quenching distance (d_{q2}) obtained by using the two parallel plates could be calculated as follows considering the balance of heat generated and heat loss inside the flange;

$$d_{q2} = \sqrt{\frac{2}{3}\frac{\lambda_b}{C_{pb}\rho_u S_u}(D + 2\delta)} \tag{1}$$

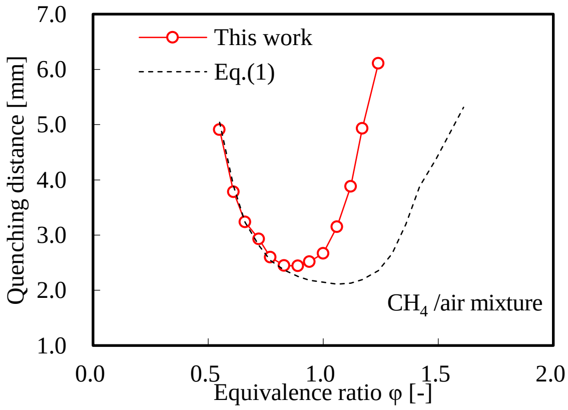
$$\delta = \frac{2\lambda_b}{C_{pb}\rho_u S_u}$$

where λ_b is the thermal conductivity of the burned gas, C_{pb} is the specific heat of the burned gas, ρ_u is the unburned gas density, S_u is the burning velocity, δ is the thickness of the flame zone. Note that there is a temperature gradient in this flame zone. The thermal conductivity λ_b was estimated using the modified Eucken equation [7], the specific heat C_{pb} was estimated using the NASA polynomial equation [8], and the burning velocity S_u was estimated using Cantera (USC-Mech[9] was used for the reaction mechanism.).

Fig.4 shows a comparison between the present experimental results and the flame quenching distance predicted from Eq.(1). It was confirmed that the present experimental results agreed well with the predicted values in the region where $1.0 \leq \phi$ for propane/air premixtures and $\phi \leq 0.8$ for methane/air premixtures. However, in the outer range of these equivalence ratios, it can be seen that the predicted value is smaller than the experimental results.



a) C_3H_8 /air mixture



b) CH_4 /air mixture

Fig.4 Dependence of quenching distance on equivalence ratio for methane/air and propane/air mixtures.

3.2 Comparison with another prediction model

Lavoie [3] arranged the measured quenching distance using the Peclet number (*Pe*) which was the ratio of advection rate of heat and thermal diffusivity as shown in Eq.(2), and its characteristics were examined.

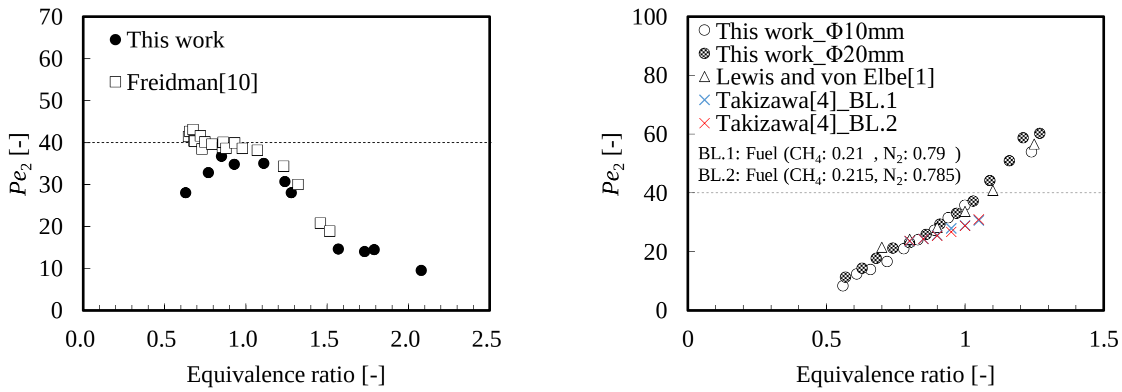
$$Pe = \frac{C_p\rho_u S_u}{\lambda_b / d_{q2}} = const. \approx 40 \tag{2}$$

Fig.5 shows the relationship between *Pe* which was calculated by substituting the results of the quenching distance obtained by the present experiment and other researchers with the value of d_{q2} in Eq.(2) and the equivalence ratio. Fig.6 shows the relationship between predicted d_{q2} by Eq.(2) and the experimental results. It was confirmed that $Pe \approx 40$ as shown in Eq.(2) was held in the region where $\phi \leq 1.0$ for propane/air premixture, but showed a decreasing trend in the fuel-rich region.

Eq.(2) means that d_{q2} and S_u are in an inversely proportional relationship. Note that one-dimensional flame propagation is assumed in deriving Eq.(2). Therefore, the effect of heat loss due to contact between the flame kernel and the flange is not described in Eq.(2). On the other hand, Eq.(1) is derived from the two-dimensional balance of heat generation due to the reaction and heat loss due to the convection and conduction from the flame kernel propagating between parallel flanges, so dq_2 depends not only on the burning velocity but also on the dimensions of the flange. Therefore, as is clear from Eq.(1), the dependence of dq_2 on S_u is weaker than in Eq.(2).

From the result of Fig.5 (a), in the region $\phi < 1.0$, the data of Freidman[10] kept a constant value of approximately 40 regardless of the equivalence ratio. It was a good agreement with Eq.(2). The present experimental results also kept a constant regardless of the equivalence ratio in the region around $\phi = 1.0$ although its value was slightly smaller than 40. From the form of Eq.(2), *Pe* being a constant implies that dq_2 is inversely proportional to S_u. However, *Pe* decreased uniformly with respect to the equivalence ratio in the region $\phi > 1.0$. This implies that dq_2 increases mildly with respect to the decrease in S_u. Therefore, it seemed that predicting dq_2 well in this region by Eq.(2) was difficult. In fact, as shown in Fig. 6, a large difference can be observed between the experimental results and prediction by Eq.(2). In contrast, the prediction results by Eq.(1) are less sensitive to S_u than Eq.(2), since dq_2 includes terms inversely proportional to S_u and inversely proportional to the square root, as mentioned above. Incidentally, in this region, dq_2 was proportional to the -0.5 power of the S_u. This value of power coincided with the dependence of dq_2 to S_u described in Eq.(1), so the experimental data shows good agreement with the predictions of Eq.(1).

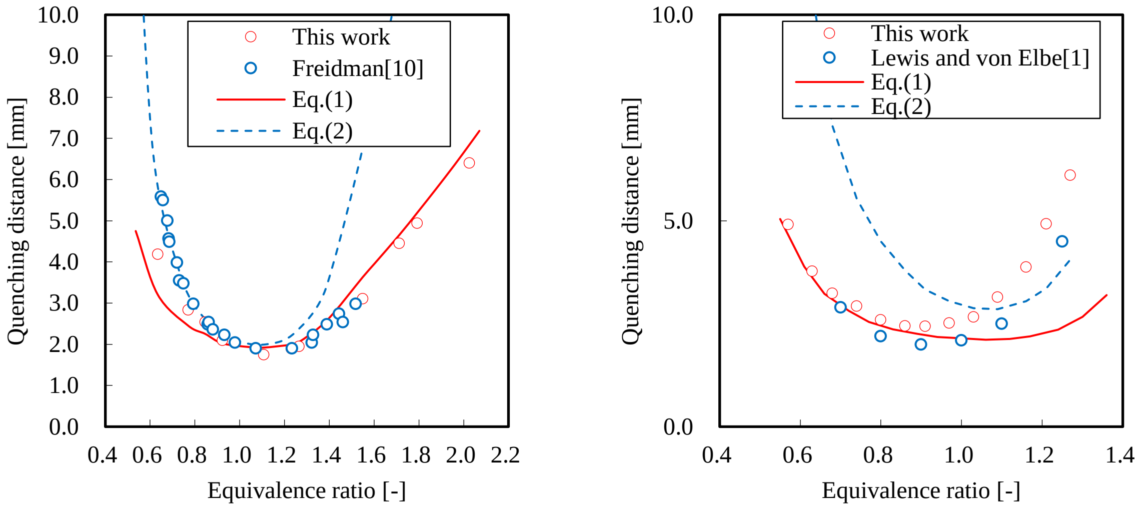
In the case of the methane/air premixture, as shown in Fig.5(b), *Pe* was no longer constant with respect to the equivalence ratio and tends to increase uniformly, so it was assumed that Eq.(2) did not give good prediction results. In fact, as shown in Fig.6(b), the predictions of Eq.(2) and the experimental results disagreed.



a) C_3H_8 /air mixture.

b) CH_4 /air mixture.

Fig.5 Equivalence ratio dependence of Peclet number for each gas species



a) C_3H_8 /air mixture b) CH_4 /air mixture

Fig.6 Relationship between d_{q2} in Eq.(2) and measurement quenching distance

3.3 Peclet number considering flange dimensions

Substituting Pe_2 into Eq.(1) which is proposed in this study, the following formula is derived. Fig.7 shows the dependence of the term in l.h.s. of Eq.(3) on the equivalence ratio.

$$Pe_2 \frac{d_{q2}}{(D+2\delta)} = \frac{C_{pb}\rho_u S_u}{\lambda_b/d_{q2}} \frac{d_{q2}}{(D+2\delta)} = const. \tag{3}$$

Eq.(3) is the product of *Pe* in Eq. (2) and $d_{q2}/(D + 2\delta)$. Since the Peclet number is the ratio of the heat transport rate by advection and the thermal diffusivity, $Pe > 1$ is necessary to promote spontaneous flame propagation. Furthermore, since the quenching distance is determined by the theory of heat transfer, it is considered that *Pe* essentially should be a constant under any conditions (composition, environment). When the flame kernel is growing up in the gap of flanges, the heat generation rate depends on d_{q2}, and the heat loss depends on the flange diameter *D*. It is considered that the term of $d_{q2}/(D + 2\delta)$ in Eq.(3) corrects the influence of this thermal balance.

From Fig. 7, $Ped_{q2}/(D + 2\delta) = 3$ to 4 in the fuel-lean region for the methane/air mixture and the fuel-rich region for the propane/air mixture, but $Ped_{q2}/(D + 2\delta)$ is increasing in other regions. It suggests that the difference of prediction and experimental results is originated not only the influence of heat loss by a flange. We found that the tendency of $Ped_{q2}/(D + 2\delta)$ against the equivalence ratio can be classified by Lewis number. It suggests that the strength of combustion influences to the quenching distance. In other words, it suggests that the burning velocity in Eq.(3) is not predicted well.

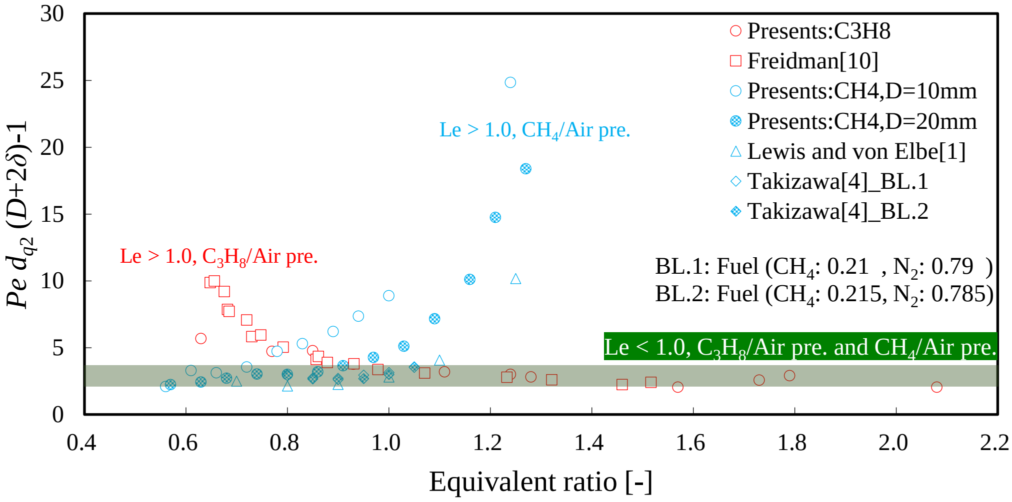


Fig.7 Concentration dependence of each gas species of $d_{q2}/(D+2\,\delta)$

3.4 Considering transient behavior of burning velocity just after ignition

As mentioned in the previous section, the change of the burning velocity immediately after ignition will have a great effect on the quenching distance. Here, an example of the time change characteristics of the burning velocity is introduced based on the analysis results of the burning velocity immediately after ignition of the hydrogen/air premixture using laser-induced breakdown ignition.

Fig.8 shows the relationship between the change of the ratio of burning velocity ($S_{\mathrm{uL}}/S_{\mathrm{u0}}$) against the flame radius at each concentration, and Fig.9 shows the dependence of the averaged burning velocity when l_{y} = 8 to 10 mm on the concentration. S_{uL} is the burning velocity which is calculated by the observable propagation rate in vertical and the adiabatic flame temperature. S_{u0} is the burning velocity calculated by Cantera. It can be seen that the burning velocity changes with time in the early stage just after the ignition, and then it reaches a converged velocity. In general, just after the ignition, $S_{\mathrm{uL}}/S_{\mathrm{u0}}$ becomes much larger than 1 due to thermal expansion depending on the energy of the ignition source. After that, it immediately decreases due to thermal diffusion. If the heat overcoming the heat loss is not generated by the combustion reaction, the flame kernel is to be quenched, but if it is generated, the burning rate is growing up again and converges to a constant value. Therefore, it is considered that the burning velocity shows a minimum value in this transition period when the ignition is observed. This trend is mainly seen in $\phi \geq 1.0$, and it can be seen that the transition period is extended as the equivalence ratio increases. In addition, it can be seen that the converged value of burning velocity takes a smaller value than the calculated value ($S_{\mathrm{uL}}/S_{\mathrm{u0}} < 1$) in the observable range of the flame diameter using the present experimental setup. Fig. 9 shows the comparison of the relationship between the value of the burning velocity and the equivalence ratio obtained in the present experiment with calculation using the GRI-Mech Model, and it can be seen that the measured burning velocity (S_{uL}) is lower than the calculated value (S_{u0}) under the condition of $\phi \geq 1.0$. This phenomenon was reported in other literature [12], and stated that the dependence of the burning velocity just after the ignition on the equivalence ratio showed a similar trend with the minimum ignition energy. If this transient behavior of the burning velocity also occurs in spark ignition between two parallel plates, it suggests that the estimation of S_{u0} may be larger than the actual value.

In summary, the quenching distance is not always inversely proportional to the burning velocity over the entire equivalence ratio, and the burning velocity estimated by Cantera might be overestimated especially in the range of Le > 1. It is expected that the quenching distance can be predicted better if the burning velocity can be predicted considering the transient behavior just after ignition.

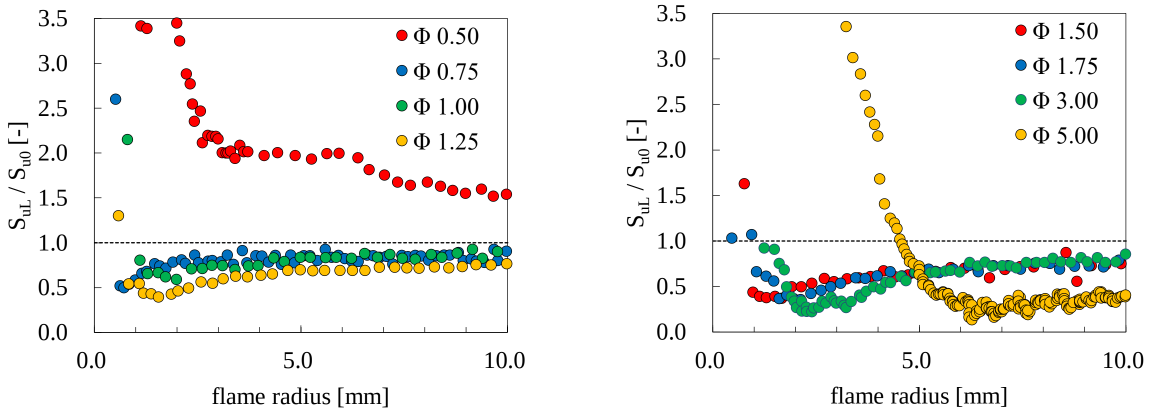


Fig. 8 Burning velocity ratio (H_2) immediately after ignition at concentration

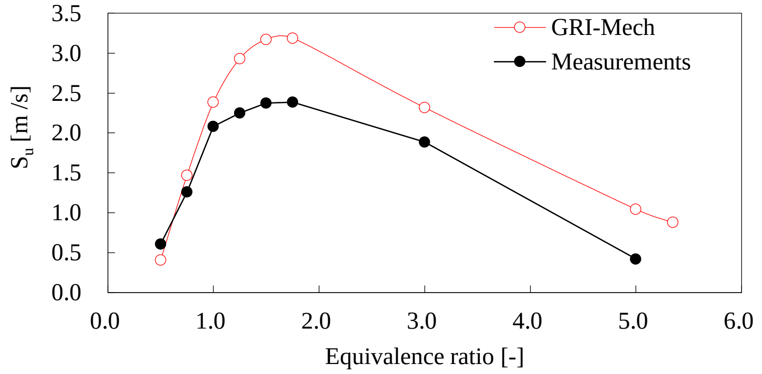


Fig. 9 Concentration dependence of average burning velocity (flame radius: 8~10mm)

4 Conclusion

In order to predict the quenching distance in the quiescent of the propane/air and methane/air mixtures more accurately, we deeply investigated by focusing on the Peclet number and burning velocity just after the ignition. We found the following conclusions.

1) The experimental results of quenching distance in $Le < 1$ could be predicted well by considering only the thermal balance, but it was not in $Le \geq 1$. In this region, Peclet number is not kept a constant value.

2) Although the flange diameter related to the heat loss of flame kernel is introduced to correct the above mismatch between the experimental and prediction results, it is not completely corrected. It suggests that the difference of prediction and experimental results is originated not only the influence of heat loss by a flange.

3) We found that the tendency of the product of Peclet number and the term to correct the heat loss influence ($Pe_2 d_{q2}/(D + 2\delta)$) against the equivalence ratio can be classified by the Lewis number. It suggests that the strength of combustion influences to the quenching distance. In fact, it was observed that the burning velocity just after ignition showed the transient behavior. It is expected that the quenching distance can be predicted better if the burning velocity can be predicted considering the transient behavior just after ignition.

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