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# DOMINANT PARAMETER TO EXTINCTION LIMIT OF PREMIXED COUNTERFLOW FLAME UNDER VARIOUS PRESSURES

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## Abstract

The dependence of extinction limit of counterflow premixed flames on pressure was experimentally and numerically investigated. Stretch rates at extinction of various mixtures with different Lewis numbers were measured in the pressure range between 0.1 MPa and 0.5 MPa. An increase in the pressure resulted in a decrease in the stretch rate at extinction of a mixture near the flammability limit. On the other hand, the stretch rate at extinction increased with pressure for a mixture with a relatively large equivalence ratio, and the maximum point appeared at a certain pressure in some cases. These changes of extinction limits with pressure did not depend on the Lewis number of the mixture. To explain those experimental results, numerical simulations using the CHEMKIN and PREMIX codes were conducted. In the analysis, it was elucidated that the Karlovitz number defined as the ratio of a characteristic chemical time and a characteristic flow time was an important factor. The characteristic chemical time was evaluated by the ratio of flame thickness and burning velocity ($\delta/S_L$), and the characteristic flow time was evaluated by the reverse of stretch rate(1/K). The dependence of stretch rates at extinction on pressure was well explained by the Ka ($Ka=(\delta/S_L)/K$). However, the Ka number evaluated from a non-stretched flame ($Ka^0=(\delta^0/S_L{}^0)/K$) failed to predict the order of stretch rates at extinction between three mixtures ( $CH_4/O_2/N_2$ flame (Le=0.97), He-20% diluted flame (Le=1.40), and $CO_2$-20% diluted flame (Le=0.90)) with the same equivalence ratio. The local Ka number ($Ka^L$) evaluated from the local burning velocity ($S_L{}^L$) and the local flame thickness ($\delta^L$) of the stretched flame was needed for precise prediction of the order of stretch rates at extinction for mixtures with different Le numbers. Therefore, the local Ka number is an appropriate criterion for predicting the quenching condition of premixed flame.

## 1 Introduction

Control of nitrogen oxides ($NO_X$) is a major issue in combustion technology. In the case of gas turbine combustors, lean-premixed combustion is considered to be suitable for such purpose and much research on this topic has been recently conducted [1,2]. Precise control of the lean-premixed combustion is also a major topic of researches of internal combustion engines such as HCCI technology [3]. Understanding of blowout points and extinction limits of flames has become very important for stable operation of lean-premixed combustors. In addition to the low emission level of $NO_x$, attainment of high combustion efficiency is also an urgent need for the design of new combustors. A high compression ratio results in high efficiency for thermal engines, and therefore the operation pressure of internal engines has become higher year and year. In spite of the importance of the pressure effect on combustion stability [1,2], the dependence of the behavior of lean-premixed flame on pressure remains unclear in this stage. Recently, Hassan et al.[4] and Gu et al.[5] revealed that the sign of the Markstein number (Ma) of $CH_4$/air flame changed with a relative small increase in ambient pressure. The increase of the Ma number results in instability of the flame.

Therefore, the understanding of flame instability is very important for the precise control of lean-premixed combustors [1,2]. On the other hand, it is well known that an increase in stretch rate of a flow suppresses flame instability [6,7], and thus the extinction limit of stretched flames under high pressure is considered to be a very complicated problem. The extinction limit of premixed flame strongly depends on the Karlovitz number (Ka), which is defined as the ratio of the characteristic chemical time scale ($\delta/S_L$, $\delta$=flame thickness, $S_L$=burning velocity) to the characteristic flow time scale (1/K, K=stretch rate). An increase in pressure results in decreases in both the flame thickness and the burning velocity, and therefore it is not easy to predict the change in the extinction limit with pressure.

In this study, the effect of pressure on the extinction limit of lean $CH_4$ flames in a counterflow field was experimentally and numerically investigated, and finally the controlling parameter for determination of the extinction limit of premixed flames at elevated pressure was studied.

## 2. Experimental Apparatus

Figure 1 shows a schematic of the experimental apparatus. Basically, the system is the same as that used in our previous papers [8,9]. The inner diameter and the length of the high pressure combustion chamber are 333.4 mm and 580.0 mm, respectively. The high pressure chamber has two observation windows, 150.0 mm in diameter. Two counterflow burners with a nozzle diameter of 9.0 mm are installed in the chamber. The separation distance between the two burners is set at 10.0 mm. When a large flow was required for extinction of flames, small burners with a nozzle diameter of 5.0 mm and a separation distance of 6.0 mm were used. To eliminate flame outside the center region of the burner, a secondary flow of $N_2$ is issued from the coaxial outer nozzle and surrounds the main flow of the mixture.

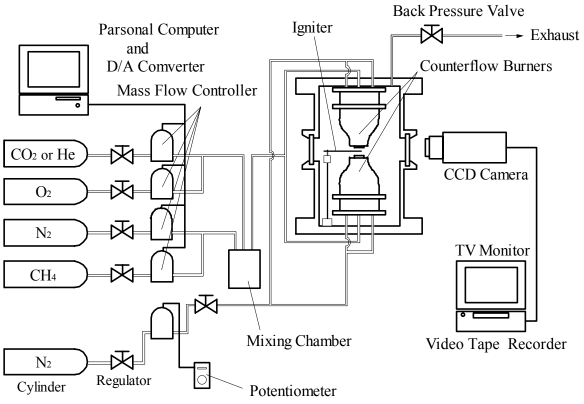


Fig.1 Schematic of experimental apparatus

A $CH_4/O_2/N_2$ mixture ($O_2:N_2$ = 21:79) as basic composition was used in the experiments. $CO_2$ and He were also used as substitutes for the $N_2$. The Lewis number (Le) was evaluated for the $CH_4$ as a deficient species in a lean mixture. Le numbers for the $CH_4/O_2/N_2$, a 20% $CO_2$ diluted mixture ($O_2:N_2:CO_2$ = 21:59:20) and a 20% He diluted mixture ($O_2:N_2:He$ = 21: 59:20) were 0.97, 0.90, and 1.40, respectively. Flow rates of each mixture were controlled by mass flow controllers with accuracy 1.0 % of full scale. The total flow rate was changed with constant mole fraction of the mixture by control of a personal computer with a D/A converter board.

The ignition of the mixture was attained by an electrically heated wire, which was remotely controlled. After establishment of twin flames, the flow rates of the mixture were gradually increased until flames disappeared. During the experiments at high pressure, the pressure in the chamber was maintained at a constant value by controlling the exhaust valve. The global stretch rate at extinction ($K_e$) in the experiment was defined as

$$K_e = \frac{2U_e}{L} \quad (1)$$

where $U_e$ is the average velocity at the exit of the nozzle at extinction and L is the separation distance between the two burners.

## 3. Results and Discussions

### 3.1 Extinction Stretch Rate at Elevated Pressures

The effect of pressure on $K_e$ was investigated in the pressure range between 0.1 MPa and 0.5 MPa. Figures 2, 3, and 4 show $K_e$ of the $CH_4/O_2/N_2$ flame, the 20% He diluted flame, and the 20% $CO_2$ diluted flame, respectively. Le numbers of those mixtures were about 0.97, 1.40, and 0.90, respectively. Basically, the dependence of $K_e$ on pressure was same for all mixtures, suggesting that the Le number does not influence the effect of pressure on extinction of premixed flames.

It is obvious in the figures that the dependence of $K_e$ on pressure changes with the equivalence ratio of the mixture. The $K_e$ increased with pressure for mixtures with relatively large equivalence ratios. On the other hand, it decreased with an increase in pressure for mixtures near the flammability limit. Full data for mixtures with large equivalence ratios under high pressure could not be obtained due to the limitation of allowable flow rates of mass flow controllers. The end data in the high pressure side suggested that flame extinction did not occur under pressure higher than that.

Figure 5 shows $K_e$ of $CH_4/O_2/N_2$ ($\phi$ =0.7) with different mole fractions of $O_2$ in the mixture. A decrease in $O_2$ mole fraction resulted in a decrease in burning velocity. As shown in the figure, the increment of $K_e$ with pressure increase became smaller as the mole fraction of $O_2$ decreased. The $K_e$ of the $CH_4$/diluted air (83% $N_2$/ 17% $O_2$) mixture became constant up to 0.5 MPa. Results shown in Figs.2,3,4 and 5 suggested that $K_e$ strongly depended on the burning velocity of the mixture. Of course, the increase in pressure also resulted in a change in the flame thickness.

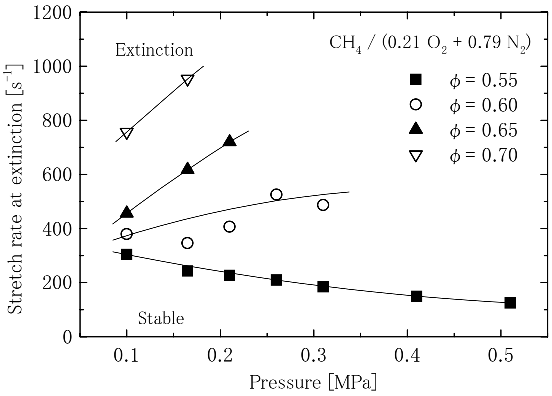


Fig.2 Effect of pressure on $K_e$ of $CH_4/O_2/N_2$ mixtures

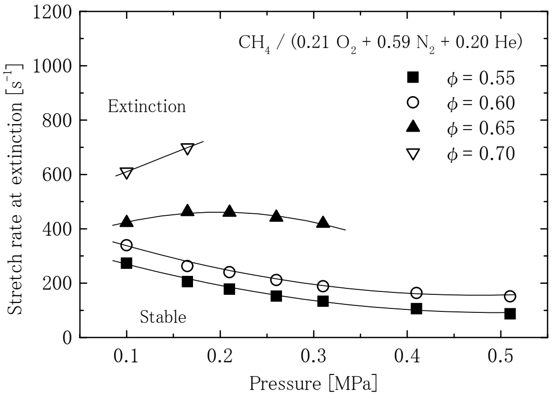


Fig.3 Effect of pressure on $K_e$ of 20% He-diluted mixtures

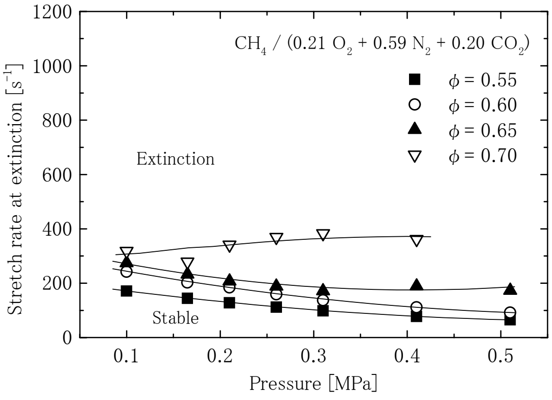


Fig.4 Effect of pressure on $K_e$ of 20% $CO_2$-diluted mixtures

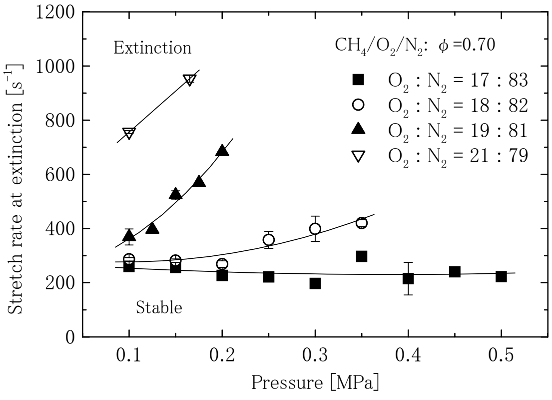


Fig.5 Effect of $O_2$ mole fraction on $K_e$ of $CH_4/O_2/N_2$ mixture

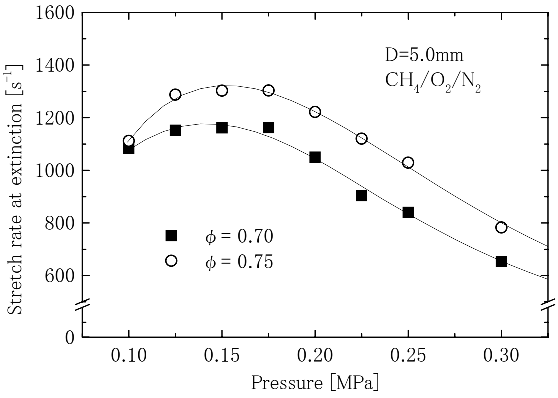


Fig.6 $K_e$ of $CH_4/O_2/N_2$ mixture measured by using small size burners (D=5.0 mm)

Flames of near stoichiometric mixture under high pressure easily reached the maximum flow rate of mass flow controllers before flame extinction. It was not clear whether flames of near stoichiometric mixtures increased continuously with pressure. To elucidate this, burners with a small diameter (D = 5.0 mm) of the nozzle exit were used for additional experiments under high pressure. The separation distance (L) between the two burners was set at 6.0 mm. Kobayashi et al. [11] showed that the ratio (L/D) of the diameter of the burner and the separation distance between burners weakly influenced $K_e$. According to their results [11], $K_e$ obtained by using small burners can be expected to become larger than that obtained by using large burners because of the increase in the ratio (L/D).

Figure 6 shows $K_e$ of $CH_4/O_2/N_2$ flames obtained by using small burners. Values of $K_e$ in Fig.6 are larger than those in Fig.2 as expected. However, the most important result was that the maximum point appeared at a certain pressure.

### 3.2 Determination of Dominant Parameter for Extinction Limit

In this section, the controlling parameter for the extinction limit of counterflow premixed flames was investigated. The Karlovitz number Ka is discussed in the following discussion.

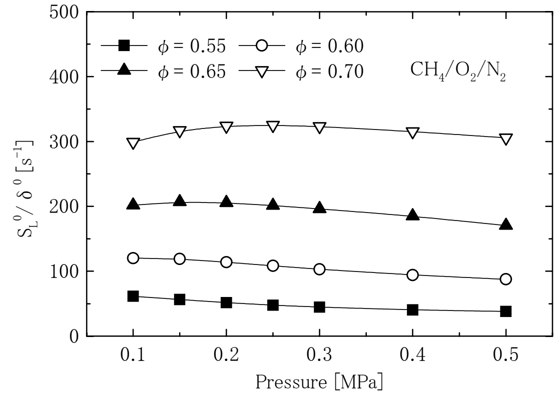
$$\mathrm{Ka} = \left( \frac{\delta}{S_L} \right) \cdot K \qquad (2)$$

The Ka number expresses the ratio of two characteristic time scales, one is a characteristic chemical time scale represented by the ratio of the flame thickness to the burning velocity ($\delta/S_L$), and the other is physical flow time scale given by the inverse of the stretch rate (1/K). To estimate the Ka number, the burning velocity($S_L^0$) and the flame thickness($\delta^0$) of the one-dimensional free propagation flame was calculated by using the PREMIX code[13].

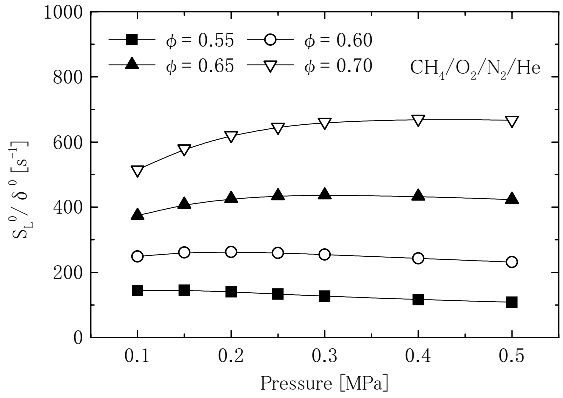
It is suggested [12] that the extinction of counterflow flames occurs when the order of the Ka number becomes O(1). Therefore, the inverse of the characteristic chemical time of the flame ($(\tau_c^0)^{-1}=S_L^0/\delta^0$) is considered to be proportional to $K_e$. Figure 7 shows $S_L^0/\delta^0$ of three mixtures at different pressures. $S_L^0/\delta^0$ of low equivalence ratio near the flammability limit decreased with an increase in pressure. On the other hand, a region where $S_L^0/\delta^0$ increased with pressure appeared for mixtures with relatively large equivalence ratios. This behavior did not depend on Le numbers of mixtures and agreed with the change in $K_e$ in the experiments as seen in Figures 2-4. However, the order of magnitude of $S_L^0/\delta^0$ between three mixtures did not agree with that of $K_e$. Figure 8 shows $S_L^0/\delta^0$ for three mixtures with the same equivalence ratio ($\phi$=0.70). The order of $S_L^0/\delta^0$ was 20% He-diluted flame, $CH_4/O_2/N_2$ flame, and 20% $CO_2$-diluted flame. There was an apparent difference from the order of $K_e$ as seen in Fig.2-4. The $K_e$ of the $CH_4/O_2/N_2$ flame is larger than that of 20% He-diluted flame. This disagreement suggests that the Ka number based on the non-stretched flame is not be able to explain strictly the behavior of flame extinction of counterflow premixed flames.

Chung et al. [14] suggested that the local Karlovitz number ($\mathrm{Ka}^L$) at extinction remained constant over a wide range of equivalence ratios of $CH_4$/air and $C_3H_8$/air mixtures. In their definition of $\mathrm{Ka}^L$, the burning velocity ($S_L$) and the flame thickness ($\delta$) were evaluated at the point of extinction.

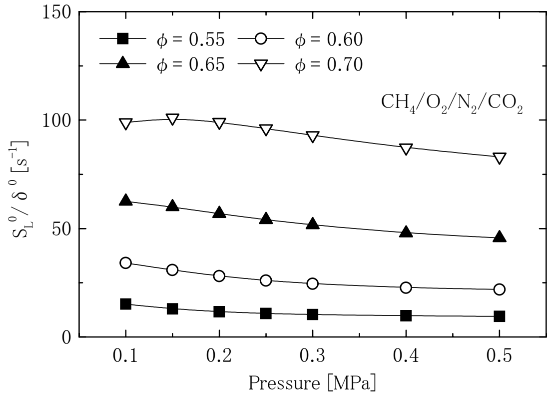
$$\mathrm{Ka}^L = \left( \frac{\delta^L}{S_L{}^L} \right) \cdot K^L . \quad (3)$$



(a)$CH_4/O_2/N_2$ mixture



(b) 20% He-diluted mixture



(c) 20% $CO_2$-diluted mixture

Fig.7 Effect of pressure on inverse of chemical characteristic time

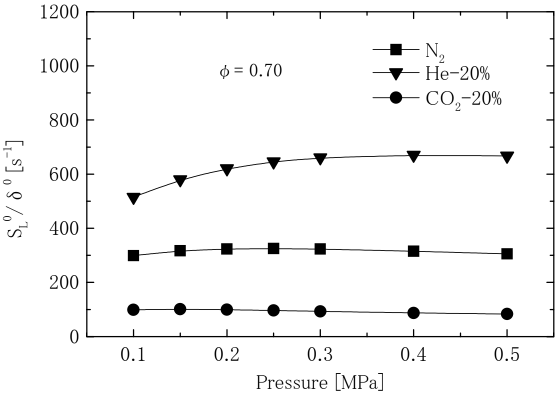


Fig.8 Comparison of inverse of chemical characteristic time between three mixtures ($CH_4/O_2/N_2$, 20% He diluted, 20% $CO_2$-diluted)

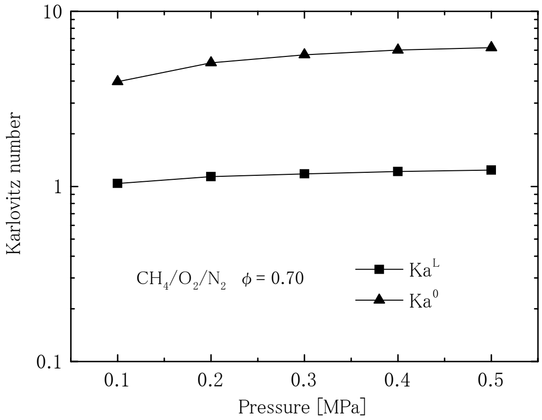
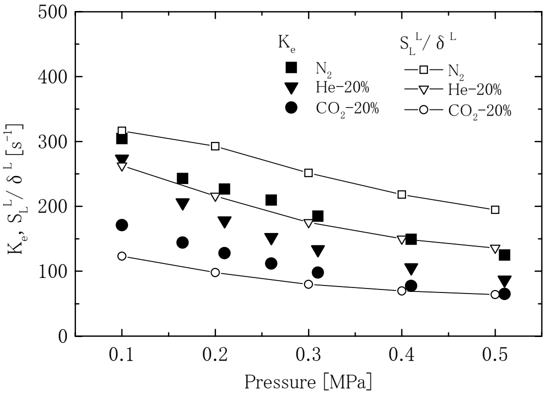
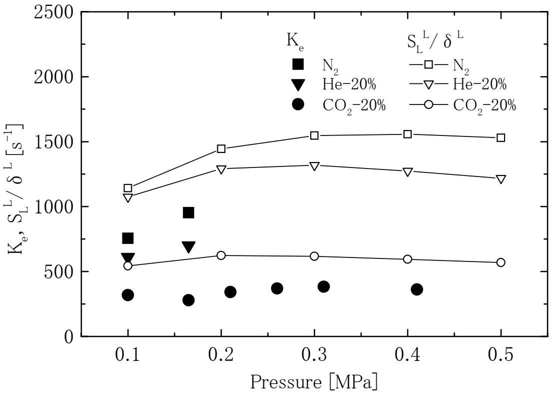


Fig.9 Comparison of Karlovitz numbers evaluated from non-stretched flame ($ka^0$) and stretched flame ($Ka^L$)

Figure 9 shows a comparison between $Ka^0$ and $Ka^L$ at extinction of $CH_4/O_2/N_2$ flames at different pressures. The $Ka^L$ is almost constant and around unity. This result shows that the $Ka^L$ is more suitable for prediction of extinction of counterflow flames than the $Ka^0$. Figure 10 shows a comparison of the inverse of the local characteristic chemical time ($(\tau_c^L)^{-1} = S_L^L/\delta^L$) at extinction and $K_e$ in the experiments. The dependence of $S_L^L/\delta^L$ on pressure that shows a different behavior between lean mixtures near the flammability limit and mixtures with a relatively large equivalence ratio agrees with that of $K_e$. In addition, the order of the inverse of $\tau_c^L$, which was $CH_4/O_2/N_2$ flame, 20% He-diluted flame, and 20% $CO_2$-diluted flame, agreed with that of $K_e$ in the experiment. This agreement was not observed in the analysis based on characteristics of non-stretched flames as seen in Fig.8. Therefore, the local extinction Ka number ($Ka^L$) is considered to be an appropriate criterion for determination of quenching of counterflow premixed flame over a wide range of experimental conditions, including pressure.



(a) ϕ=0.55



(b) ϕ=0.70

Fig.10 Comparison between inverse of local characteristic chemical time and $K_e$

## 4. Conclusion

(1) The stretch rates at extinction ($K_e$) of counterflow lean premixed flames near the flammability limit decreased with an increase in pressure. On the other hand, those of counterflow flames with relatively large equivalence ratios increased with pressure, and sometimes the maximum point appeared at a certain pressure. These tendencies did not depend on the Le number of the mixture.

(2) The dependence of $K_e$ obtained in experiments was explained well by considering the Karlovitz number (Ka) of the mixture. However, the order of magnitude of $K_e$ of the three mixtures ($CH_4/O_2/N_2$ mixture, 20% He-diluted mixture, and 20% $CO_2$-diluted mixture) with different Lewis numbers was not explained by the Ka number evaluated ($Ka^0$) from non-stretched flames. The local Karlovitz number ($Ka^L$) at extinction was more suitable for the precise estimation of the quenching condition of counterflow premixed flames than $Ka^0$.

## Acknowledgement

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