Effects of Pressure on Burning Velocity and Instabilities of Propane-Air Premixed Flames*

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Spherically propagating laminar flames at elevated pressures in a large volume bomb were studied for propane-air mixtures. The effects of the initial mixture pressure on the burning velocity and flame instabilities were investigated varying the initial pressure from 0.10 to 0.50 MPa. The Markstein number decreased with the increase in the initial pressure. The burning velocities at elevated pressures are affected not only by the change in the unstretched burning velocity but also by the variation in the Markstein number, or the variation in the sensitivity of the burning velocity to the flame stretch. The flame with a low Markstein number was unstable. Cellular flame structure developed earlier in such cases. Cellular structure accelerated the flame propagation. The burning velocity was affected by the flame instabilities in addition to the above two factors.

***Key Words*:** Premixed Combustion, Combustion Phenomena, Laminar Flame, Burning Velocity, Flame Stretch, Markstein Number, Flame Instability, Cellular Flame, Effect of Pressure

1. Introduction

In the practical combustion fields such as internal combustion engines, the flame propagates in the mixture at high pressure. There are few fundamental studies on the flame propagation at elevated pressure although the flame properties at atmospheric pressure were studied intensively.

Andrews and Bradley[(1)], Metghalchi and Keck[(2)], Iijima and Takeno[(3)], and Hill et al.[(4)] investigated the effects of the pressure on the laminar burning velocity of the spherically propagating flame. Kobayashi et al.[(5)] studied the laminar burning velocity and the flame instabilities at elevated pressures.

On the other hand, the burning velocity of the flame varies from its unstretched value even though the flame is laminar if the flame is subject to the stretch by the aerodynamic strain and/or the flame curvature. The Markstein number expresses the sensitivity of the burning velocity change to the flame stretch rate[(6)−(21)]. The reduction in the laminar burning velocity from the unstretched one due to the stretch is proportional to the flame stretch rate, and the Markstein number is the proportional constant.

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Spherically propagating laminar flame is subjected to the flame stretch. Bradley et al.[(16),(17)] and Faeth et al.[(18),(19)] showed that the change rate of the burning velocity or the Markstein number varied by the pressure. Müller and Peters et al.[(20)] and Law et al.[(21)] also showed the pressure dependency of the Markstein number.

Because the unstretched laminar burning velocity is affected by the pressure, the burning velocity of the stretched laminar flame is affected by the pressure in two ways, the variation in the unstretched laminar burning velocity and the variation in the sensitivity of the burning velocity to the flame stretch.

As shown by Bradley and Kitagawa et al.[(22)], the burning velocity of the turbulent flame also depended on the pressure. The decrease in the Markstein number increased the turbulent burning velocity. It might be due to the flame stretch by turbulence. For these reasons, it is important to investigate the effects of the pressure on the relationship between the laminar burning velocity and the flame stretch.

Flame was unstable under the condition of low Markstein number[(23)]. Low Markstein number was indicative of the flame instabilities. Cellular flame structure developed earlier in such cases.

The flame is no longer stabilized by the flame stretch at the large flame radius though the positive flame stretch will restrain the Darrieus-Landau flame instability. Especially, the flame with the negative Markstein number is unstable even at the small flame radius.

The transition to the cellular flame became earlier as the Markstein number decreased. The cell size became smaller the Markstein number decreased. The Markstein number decreased with the increase in the pressure, the flame was more unstable at elevated pressures. The cellular structure will affect the burning velocity.

In this study, the effects of the initial mixture pressure on the burning velocity and the flame instabilities were investigated for outwardly propagating spherical laminar flames in a large volume bomb varying the initial pressure from 0.10 to 0.50 MPa. The large combustion chamber of 35 000 cm^3 enabled the flame propagation up to larger flame radius with smaller flame curvature than the other studies. The burning velocity was derived from the pressure record in the bomb though it was obtained from the flame radius of the shadow or schlieren image in the most of other studies on propagating flame in the bomb. The burning velocity by pressure measurement concerns the rate of mass burning.

The burning velocity began to increase rapidly by the formation of the cellular flame in the case of small Markstein number. The timing at the onset of this acceleration was almost consistent with the timing at which the whole of the spherical flame was covered with cells.

The burning velocity was affected by the flame instabilities in addition to the two factors related to the pressure change, the change in the unstretched burning velocity, and the variation in the Markstein number.

2. Markstein Number

Spherically propagating flame is subjected to the flame stretch due to the curvature of the flame front. And its burning velocity varies accompanied with the change in the curvature during the explosion.

The variation in the stretched laminar burning velocity, u_n from the unstretched one, u_l is given by Eq. (1).

$$u_l - u_n = L \cdot \alpha \tag{1}$$

Here the variation in the laminar burning velocity due to the flame stretch is proportional to the stretch rate, α[(9)−(12)]. And L is the Markstein length.

The flame stretch rate, α imposed on the spherically propagating flame is calculated by the flame front area A, or the flame radius, r according to Eq. (2)[(6),(8),(13)].

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r}\frac{dr}{dt} = \frac{2}{r}S_n \tag{2}$$

Here, S_n (= dr/dt) is the flame propagation speed[(13),(16),(20)].

Then the unstretched laminar burning velocity, u_l was deduced by the extrapolation of the stretched laminar burning velocity to zero stretch rate.

Equation (1) is non-dimensionalized by the unstretched laminar burning velocity and the laminar flame thickness, δ_l:

$$\frac{u_l - u_n}{u_l} = K \cdot Ma \tag{3}$$

in which K is the flame stretch factor and Ma is the Markstein number[(16)]. And the laminar flame thickness, δ_l is

$$\delta_l = \frac{\lambda}{Cp \cdot \rho \cdot u_l} \tag{4}$$

where Cp, λ and ρ are the specific heat at constant pressure, thermal conductivity and density of the mixture respectively.

Flame radius, r was calculated from the pressure, P in the bomb according to Eq. (5)[(23)].

$$\frac{r}{r_v} = \left[1 - \left(\frac{P_i}{P}\right)^{\frac{1}{\gamma}} \frac{P_m - P}{P_m - P_i}\right]^{\frac{1}{3}} \tag{5}$$

where P_i and P_m are the initial and maximum pressure, respectively. The maximum pressure, P_m was obtained by the chemical equilibrium calculation in the constant volume condition. γ is the specific heat ratio of the mixture. P_m and γ were calculated by CHEMKIN package[(24)]. r_v is the radius of the chamber and is 20.3 cm in this study.

The stretched burning velocity, u_n of the propagating flame was obtained by Eq. (6)[(25)].

$$u_n = \frac{r_v}{3 \cdot (P_m - P_i)} \cdot \left(\frac{P_i}{P}\right)^{\frac{1}{\gamma}} \times \left[1 - \left(\frac{P_i}{P}\right)^{\frac{1}{\gamma}} \cdot \frac{P_m - P}{P_m - P_i}\right]^{-\frac{2}{3}} \cdot \frac{dP}{dt} \tag{6}$$

The flame stretch rate, α and the stretched burning velocity, u_n were calculated from the pressure by Eqs. (2), (5) and (6). Then the Markstein length, L was determined by applying Eq. (1) to the relationship between α and u_n measured during the explosion.

The unstretched laminar burning velocity, u_l was also derived as the intercept value of u_n at $\alpha = 0$ or $r \to \infty$.

The propagating flame was supposed spherical and smooth in these procedures. In some cases, however, this assumption was not able to apply because of the flame instability discussed later. Nevertheless these values were estimated for all the cases[(23)].

3. Experimental Apparatus and Procedures

3.1 Explosion bomb and procedures

Experiments were carried out using a constant volume bomb as shown in Fig. 1. The combustion chamber was an interpenetration shape of three cylinders of 265 mm diameter. The volume of the chamber was about 35 000 cm^3 and was equivalent to the sphere of 40.6 cm diameter.

Mixture was prepared in the chamber according to the partial pressure of each component. It was mixed well by two fans equipped at the top and bottom of the chamber. The mixture was ignited by the electric spark at the center of the chamber after the mixture became quiescent.

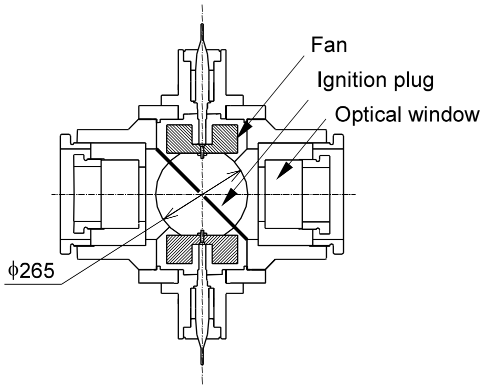

Fig. 1 Schematic figure of combustion chamber

The pressure history was recorded by a pressure transducer. Flame propagation was observed by the schlieren photography technique through two optical windows of 160 mm diameter.

3.2 Experimental conditions and properties of mixtures

Propane-air mixtures were studied at initial pressures P_i of 0.10, 0.25 and 0.50 MPa. The equivalence ratio, ϕ was set to 0.8, 1.0 and 1.3. The initial temperature of the mixture was 298 K.

The unstretched laminar burning velocity, u_l and the Markstein number, Ma obtained in the previous study[23] are shown in Table 1. The unstretched laminar burning velocity, u_l decreased as the initial pressure, P_i increased. The Markstein number, Ma decreased as the equivalence ratio, ϕ increased at all the initial pressure. It decreased as the initial pressure increased at all the equivalence ratios. This means that the sensitivity of the change in the burning velocity to the flame stretch was varied by the initial mixture pressure.

The Markstein number was negative at the equivalence ratios of 1.3 when the initial pressure was 0.25 and 0.50 MPa. The stretched laminar burning velocity increased by the flame stretch in these cases.

The burning velocity of the stretched laminar flame is affected by the pressure in the two ways. One is the variation in the unstretched laminar burning velocity, u_l by the pressure change. The other is the variation in the sensitivity of the burning velocity to the flame stretch, or the variation in the Markstein length by the pressure change.

Table 1 Measured unstretched laminar burning velocity, u_l and Markstein number, Ma

P_i MPa	ϕ	u_l cm/s	Le	Ma	δ_l mm
0.10	0.8	27.7	1.81	7.25	0.075
	1.0	39.7	—	7.01	0.051
	1.3	38.5	0.96	5.58	0.052
0.25	0.8	22.3	1.81	6.15	0.038
	1.0	35.7	—	5.62	0.023
	1.3	27.8	0.96	-3.10	0.029
0.50	0.8	19.9	1.81	3.85	0.021
	1.0	32.1	—	2.81	0.013
	1.3	24.1	0.96	-7.10	0.017

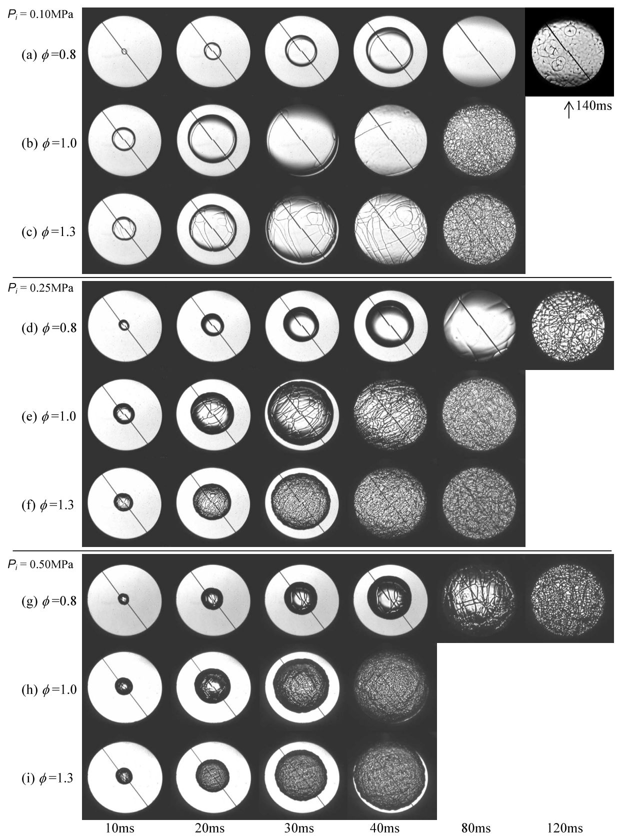

Fig. 2 Schlieren images of flames

4. Experimental Results and Discussion

4.1 Observation of spherically propagating laminar flame

Figure 2 shows the schlieren images of the flame at the equivalence ratios of 0.8, 1.0 and 1.3. Time in the figure denotes the elapsed time from the ignition.

When the initial pressure was 0.10 MPa, no cracks except for ones due to the spark plug were observed in the early stage of the explosion at $\phi = 0.8$ and 1.0. On the other hand, some cracks were formed at $\phi = 1.3$. The flame became cellular in the middle of the explosion at $\phi = 1.3$. The rich flame was unstable for the propane mixture.

Cracks were formed earlier in each case as the initial pressure increased. When the initial pressure was 0.25 MPa, the whole of the flame was covered with small cells soon after the ignition at $\phi = 1.3$. Some cracks were also formed in the early stage of the explosion at $\phi = 1.0$. When the initial pressure was 0.50 MPa, the flame was cellular soon after the ignition at $\phi = 1.3$. Cracks were also observed in the early stage even at $\phi = 0.8$.

Cracks increased and the distance between cracks and cell size became small as the flame propagated.

4. 2 Variation of burning velocity by flame instabilities

The flame instabilities seemed to affect the burning velocity because the flame surface area might be changed by the formation of the cracks and cells. Figure 3 shows the variation of the stretched burning velocity, u_n with time during the explosion at the initial pressures, P_i of 0.10 and 0.50 MPa. It was analyzed within the pressure rise up to about 5% of P_m. In the figure, u_n was shown as the ratio to the unstretched laminar burning velocity, u_l.

When the initial pressure, P_i was 0.10 MPa, the burning velocity increased gradually with time at $\phi = 0.8$. It was smaller than the unstretched laminar burning velocity within the analyzed period. At $\phi = 1.3$, it began to increase rapidly about 45 ms from the ignition though it increased gradually in the early stage of the explosion. It exceeded the unstretched value after its rapid increase though the Markstein number was positive. The timing of this transition was almost consistent with the timing at which the whole of the spherical flame was covered with cells uniformly. When the initial pressure, P_i was 0.50 MPa, the burning velocity at $\phi = 1.3$ also increased soon after the ignition. The transition timing was quite earlier than the case of $P_i = 0.10$ MPa.

4. 3 Transition to cellular flame

As shown above, the laminar burning velocity was affected by the flame instabilities. So the properties of the flame instabilities were investigated.

Figure 4 shows the critical Peclet number, Pe_{cl} at the transition to the cellular flame from the smooth laminar one. The flame was considered to become cellular when the cracks were formed uniformly on the flame front. This figure shows only the data that the flame became cellular within the pressure rise up to about 5% of P_m. Pe_{cl} in the case that the transition took place far above the initial mixture pressure was not indicated. The flame of $\phi = 0.8$ became cellular at 140 ms from the ignition when the initial pressure was 0.10 MPa in Fig. 2. This transition might be due to the large pressure increase beyond this limit.

Cracks were formed earlier as the equivalence ratio increased. And the increase in the initial pressure advanced the timing of the onset of cracks.

Low Markstein number was indicative of the flame instabilities because the Markstein number was small for the rich propane mixtures at high initial pressures. As the flame propagated, cracks increased and then the flame became cellular. Cellular flame structure[26] developed earlier in such cases[27]. Especially, the flame with the negative Markstein number was cellular soon after the ignition.

Outwardly propagating spherical laminar flame is convex to the unburned gas. It is subjected to the positive flame stretch. When the Markstein number has the large positive value, the flame is stable to the Darrieus-Landau flame instability[11]. The thermal-diffusion effect seems to stabilize this hydrodynamic instability.

When the convex and concave parts are formed on the flame front by some perturbation, the burning velocity in the convex part to the unburned gas will be reduced by the increase in the flame stretch and that in the concave part will be increased. The perturbation will be suppressed. Then the flame with large positive Markstein number will be stable.

The flame, however, is no longer stabilized by the flame stretch at the large flame radius because the flame stretch rate is reduced by the small curvature. The flame stretch rate is too small to restrain the Darrieus-Landau flame instability at the large flame radius. Then the cracks are formed and the laminar flame will become cellular.

As for the thermal-diffusion effect, it is related to the Lewis number. The Lewis number based on the diffusion coefficient of the deficient reactant is shown in Table 1. The Lewis number, however, is independent of pressure and gives no indication of the pressure effect on instabilities. Nevertheless, the Markstein number is correlated to the Lewis number[28]. The values of the Markstein numbers were small for the mixtures those of the Lewis number were almost unity or less than it.

When the Markstein number is small and positive, the flame stretch will not suppress the flame instability so much because the variation of the burning velocity due to

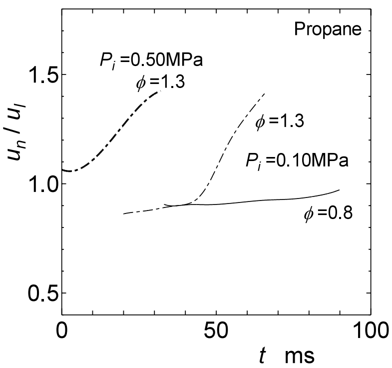

Fig. 3 Variation of burning velocity, u_n

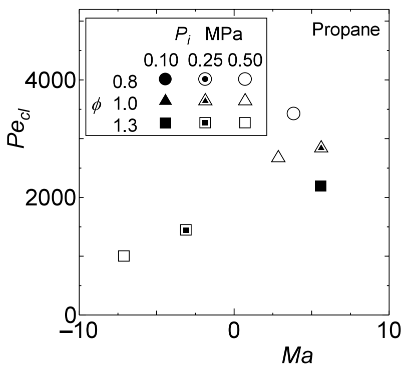

Fig. 4 Critical Peclet number, Pe_{cl}

the flame stretch is small. The flame instability is more notable than the flame with the large Markstein number[29].

Especially, the flame with the negative Markstein number is unstable even at the small radius. The thermal-diffusion effect will also make the flame unstable.

4. 4 Scale of flame instabilities

The distance between cracks and cell size in Fig. 2 were different from each other case of the equivalence ratio and the initial mixture pressure. The cell size will affect the flame front area and local flame stretch. These will lead the increase in the burning velocity.

Here, the non-dimensional wave number of the flame instability, N_{sc} was obtained from the measured distance between the cracks on the schlieren image though this distance does not coincide with the wave length of instability because of the line sight integration effect of schlieren technique.

$$N_{sc} = \frac{2\pi \cdot Pe}{\Lambda_{sc}} \tag{7}$$

where Λ_{sc} is the non-dimensional wave length. Λ_{sc} was the measured distance of cracks normalized by the laminar flame thickness, δ_l.

Figure 5 shows the mean wave number, $N_{sc,a}$ obtained by the arithmetical mean of the measured wave number of cells at each flame radius when the initial pressure was 0.50 MPa. The mean wave number of the instability increased with the flame propagation at all the cases of the equivalence ratios.

As the flame propagated, the number of cracks increased gradually. The distance between cracks and the cell size consequently decreased.

Bradley et al.[30] showed by the PLIF images of cellular flames that cusps toward the burned gas were formed on the flame. The curvature of the flame front increased in the part fractured by the cusps.

Once the cracks are formed, the flame front fractured by the cracks is restabilized because the stretch rate is increased. As the flame propagates increasing in its size, the flame stretch is reduced to unstable rate. Then the new cracks will be formed again. So $N_{sc,a}$ increased continually with Pe.

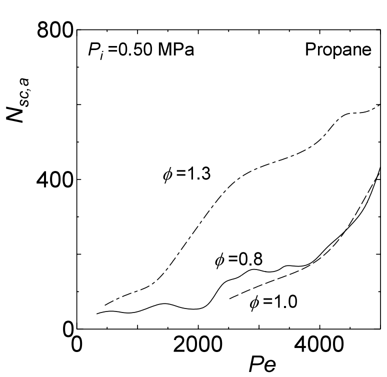

Fig. 5 Variation of wave number, $N_{sc,a}$ with ϕ

The wave number, $N_{sc,a}$ was largest at the equivalence ratio of 1.3 among three equivalence ratios of 0.8, 1.0 and 1.3.

Figure 6 shows the effects of initial mixture pressure on the wave number, $N_{sc,a}$ at $\phi = 1.3$. The wave number increased as the initial mixture pressure increased. As the flame thickness, δ_l decreases with the increase in the pressure as shown in Table 1, the flame could be perturbed up to the smaller wave length.

Because the Markstein number decreased with the increase in the initial pressure, this wave number seemed to increase as the Markstein number decreased. Flame instabilities were correlated with the Markstein number.

The increase in the burning velocity might be caused by the increase in the flame surface area due to the instabilities. If the Markstein number was small, the increase in the local stretch rate by cells might also accelerate the flame. Figure 7 shows the pressure histories when the initial mixture pressure, P_i was 0.50 MPa. Pressure rose faster in the middle of the explosion at $\phi = 1.3$ than $\phi = 1.0$, though the unstretched laminar burning velocity, u_l at $\phi = 1.3$ was smaller than $\phi = 1.0$[23]. The Markstein number at $\phi = 1.3$ was smaller than that at $\phi = 1.0$ and it was negative. The flame at $\phi = 1.3$ became cellular faster and its cell size was smaller than $\phi = 1.0$. The burning velocity of the flame at $\phi = 1.3$ after the cellular transition increased largely due to the cellular flame structure.

The Markstein number is related to the Lewis num-

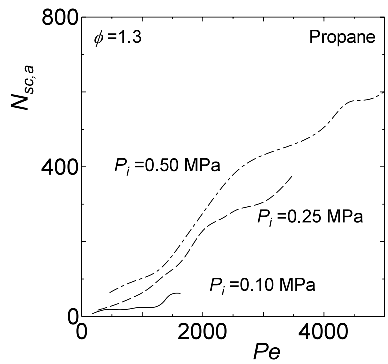

Fig. 6 Variation of wave number, $N_{sc,a}$ with P_i

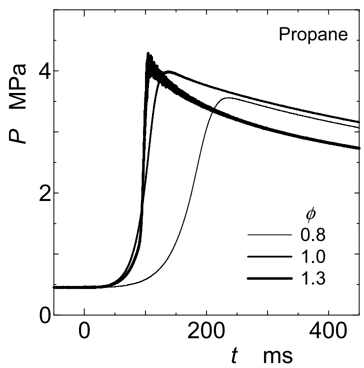

Fig. 7 Pressure histories at $P_i = 0.50$ MPa

ber[11],[29]. The reason why the Markstein number varies with pressure is not so clear, yet. However, both pressure and thermal-diffusion effects on the premixed flame could be discussed with the Markstein number in this study.

5. Conclusions

Spherically propagating laminar flames in a large volume bomb were studied. The effects of the initial mixture pressure on the burning velocity and the flame instabilities were investigated varying the initial pressure from 0.10 to 0.50 MPa.

Spherically propagating flame is subjected to the flame stretch. And its burning velocity and stretch rate varies during the explosion. The contribution of the flame stretch to the laminar burning velocity is quantified by the Markstein number.

Cracks due to the flame instabilities were formed on the flame front. As the flame propagated, cracks increased and then the flame became cellular. Low Markstein number was indicative of the flame instabilities. Cellular flame structure developed earlier in such cases. The critical Peclet number at the transition to the cellular flame was found to decrease as the Markstein number decreased. The non-dimensional wave number of the instability increased with the flame propagation. This wave number increased as the Markstein number decreased.

The burning velocity began to increase rapidly by the formation of the cellular flame in the case of small Markstein number. It exceeded the unstretched value after its rapid increase even in the case that the Markstein number was positive. The timing at the onset of this acceleration was almost consistent with the timing at which the whole of the spherical flame was covered with cells.

The burning velocity was affected by the flame instabilities in addition to the two factors related to the pressure change, the change in the unstretched burning velocity, and the variation in the Markstein number.

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