Study of laminar flame speed measurement under high pressure condition using double kernel method by laser-induced breakdown ignition

Takehiko SEO*, Hirotsugu KANEKO* and Masato MIKAMI*

*Graduate School of Sciences and Technology for Innovation Yamaguchi University
2-16-1 Tokiwadai, Ube, Yamaguchi, 755-8611, Japan
E-mail: tseo@yamaguchi-u.ac.jp

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Abstract
In order to understand turbulent combustion and its characteristics, laminar flame speed is often used. Laminar flame speed plays an important role in turbulent combustion models used in engine combustion simulation. However, there are few reports on laminar flame speed of liquid fuel under high pressure condition simulating the inside of an engine cylinder. In this study, the measuring system using simple compact equipment was developed to obtain laminar flame speed of liquid fuel with the double kernel method under high pressure conditions. In this equipment, as easily ignited at high pressure, laser induced breakdown ignition technique was used. The experiments were conducted on propane-air premixed gas so that it could be easily compared with the reports of other researchers. The experiment was conducted on propane/air premixture so that it could be easily compared with the other reports. A detailed investigation of the time history of the flame separation revealed that the conventional method of calculating the laminar flame speed used in the double kernel method was not suitable for this measuring system. Therefore, a new calculation method for the laminar flame speed was studied, and the pressure dependence of the laminar flame speed of the propane/air premixture was investigated. As a result, it was found that it was in good agreement with other reports. The laminar flame speed measurement system developed in this study is considered to be useful.

Keywords: Laminar flame speed, Double kernel method, High pressure condition, Laser induced breakdown ignition, Measuring system

1. Introduction

As energy resources become depleted and global warming increases, the need for the development of highly efficient combustion technology is increasing to enhance the efficiency of internal-combustion engines of automobiles. For this purpose, it is necessary to obtain detailed knowledge of turbulent combustion and its characteristics under high temperatures and high pressure conditions in engine cylinders.

Laminar flame speed is often used to understand turbulent combustion and its characteristics. For example, it is used to derive the Karlovitz Number, which is a parameter to classify velocity scales and combustion types of premixed flames in the turbulent combustion diagram proposed by Peters (Peters, 2000). Also in verification of the reaction mechanism used in combustion simulation and development of combustion models, the laminar flame speed plays an important role and is used as a reference to calculate the turbulent combustion velocity. The laminar flame speed is one of the most fundamental physical property values in clarification and analysis of combustion phenomena.

The laminar flame speed has been measured by using various flames such as burner flames (Ruan et al., 1999), counter-flow flames (Yu et al., 1986), (Davis et al., 1998) and spherical propagation flames. In particular, for measurement of laminar flame speed under high pressure, the spherical flame propagation method using a constant volume chamber (Kitagawa, 2009), (Jerzembeck et al., 2009), (Tanoue et al., 2012) has been widely used. Since the influence of flame elongation as time passes has to be taken into account to measure the laminar flame speed using
spherically propagating flames, it is preferable to make measurements after flames have grown sufficiently. If the pressure in a vessel changes during flame propagation, the influence of the change needs to be taken into account, and therefore a large constant-volume chamber with sufficient capacity and pressure resistance is often used for experiments. Since higher compression ratios have been used in recent years to realize higher efficiency of internal-combustion engines of automobiles, larger experimental equipment is needed to determine the laminar flame speed under these conditions and experiments would be difficult depending on the safety and cost. A spark from electrodes is usually used for ignition of experimental equipment. However, since high pressure increases both the density of a gas between the electrodes and the voltage necessary for electric discharge, stronger ignition equipment is necessary for experiments. Therefore, if one can establish a laminar flame speed measurement method using a simple compact test unit to solve the problems related to using large equipment and ignition systems, it would contribute to the future needs for understanding the combustion characteristics under high pressure conditions.

Raezer et al. (Raezer et al., 1962) developed a double kernel method for measurement with compact equipment. The double kernel method ignites fire simultaneously at two points separated by an appropriate distance on the same axis in a constant-volume chamber and the burning velocity is calculated by measuring the distance between the flame fronts approaching each other. One advantage of this method over the spherical flame propagation method is that the burning velocity can be measured under high pressure conditions in a compact constant-volume chamber because the flame fronts approaching each other are relevant. Andrews et al. (Andrews et al., 1978) calculated the laminar flame speed of hydrogen, methane and air premixture by linear approximation of temporal change of the flame separation immediately before they contacted each other. The results are in good agreement with the nozzle burner, Schlieren angle, and particle track method of measurement. Moreover, pressure dependence up to 3 atm of a methane air premixture was studied. Yamazaki et al. (Yamazaki et al., 2000) studied the flame separation used in a polynomial approximation and the order of the polynomial for calculation of the laminar flame speed. Using a second order polynomial, they approximated the time dependence of the flame separation for the separation of 9 mm or shorter after ignition and determined the laminar flame speed from a half of the gradient of the approximated line immediately before the flame fronts contacted each other. They reported that the laminar flame speed could be derived within a systematic error of 10%. In addition, for methane air premixture with pressure up to 3 atm and temperature up to 400 K, they studied the temperature dependence and pressure dependence of the laminar flame speed.

In this study, laser ignition was adopted as a method for reliable ignition system under high pressure conditions. Laser ignition can also create laser-induced plasma, which triggers ignition, rather easily under high pressure conditions. With laser ignition system, it is possible to avoid misfiring, which is a problem when using the spark ignition system under high pressure conditions.

In this study, the measuring system for laminar flame speed using simple compact equipment with the double kernel method using laser induced plasma as the ignition source was developed. Before measuring the laminar flame speed of a liquid fuel under high pressure conditions, we measured the laminar flame speed with high pressure for propane/air premixture, which is a gas fuel for which the speed has been reported in many articles. For the measurement, we used the propane/air premixture with the equivalent ratio of 1.0, room temperature of 298 K, and initial pressure up to 1.0 MPa. Then, we developed a laminar flame speed calculation method using the developed test equipment.

2. Experimental apparatus and procedure

Figure 1 shows the constant volume chamber used in the study. The chamber is of a cylindrical shape with a diameter of 80 mm and a width of 50 mm. There are observation windows on the front and rear sides of the chamber for optical measurement of flames. On both sides of the chamber, there are plano-convex lenses (SQ, Sigmakoki) for laser beams coming through the lenses to converge and ignite inside the chamber. The capacity of the chamber, including a dead volume such as a valve, is 292 cc. A pressure transducer (PGL-A-20MP-A, Kyowa) attached at the lower part of the chamber is for measurement of pressure history during combustion. On the upper left of the chamber, a temperature sensor for measurement of the temperature inside the chamber and a valve with pressure transducer (PGL-A-5MP-A, Kyowa) for measurement of the filling pressure are installed. On the upper right of the chamber, a rapture disk (Type U, V TEX) is installed to prevent damage to the observation windows and laser incident windows due to pressure increase during combustion. Although not used in the experiment, a mixer (Suzukirika) is installed on
the upper part of the chamber and a cartridge heater (CT16-125, Nippon Heater) is attached to the lower part of the chamber to control the initial temperature. A fixed amount of propane and air is supplied to the chamber by using a partial pressure method to form a premixed gas with the equivalence ratio of 1.

Figure 2 shows the ignition system used for the laser induced plasma. The 532 nm second harmonic of Q switch Nd:YAG laser (GCR-130-10, Spectra Physics) was used as the laser source. A laser beam was divided through a 1/2 polarizing plate and a polarization beam splitter into S polarization and P polarization beams. Each beam converged through the plano-convex lenses facing each other on the sides of the constant-volume chamber to generate the plasma used as the ignition source. Ignition at two points on the same axis, which is necessary for the double kernel method, can thus be made. Flame behavior was observed with Schlieren imaging technique using pulsed diode laser light source (CAVILUX Smart, Nobby Tech) and a high-speed CMOS camera (Phantom v9.0, Vision Research Inc.). Considering the laminar flame speed under various pressure conditions, the image shooting speed was changed in the range from 800 fps to 2000 fps depending on the conditions so that the flame could move by about 15 pixels in a single frame. In each frame, a phenomenon was recorded for 50 ns, which was the illuminating time period of the laser light for visualization. Consequently, the calculation error of the laminar flame speed due to erroneous detection of a pixel was within 7%. The spatial resolution was about 16 μm/pix.

3. Analytical method
3.1 Principle of double kernel method

The concept of the double kernel method is shown below. In Fig. 3, let $S_{u1}$ and $S_{u2}$ be the laminar flame speed and $V_{g1}$ and $V_{g2}$ be the velocities of unburned premixture due to expansion of burned gas. Then the flame propagation velocities $V_{f1}$ and $V_{f2}$ of two flames formed in the premixture are given by the following formula.
When the two flame fronts approach each other, a stagnation point between the flame fronts causes the expansion velocity of the unburned premixture \( V_g \) to be 0 and the flame propagation velocity \( V_f \) becomes equal to the laminar flame speed \( S_u \). Therefore, we have the following two equations.

\[
V_{f1} = S_{u1} + V_g1
\]

\[
V_{f2} = S_{u2} + V_g2
\]

The laminar flame speed of the premixture \( S_u \) when the two flame fronts approach each other is given by the following where the flame separation is denoted by \( x \).

\[
S_u = -\frac{1}{2} \frac{dx}{dt} \bigg|_{x=0}
\]

### 3.2 Influence of pressure increase during combustion

Pressure in the chamber could increase during combustion. In the study, since the measurement finishes at the moment when the two flames contact each other, the pressure increase in the period from the ignition to the contact of flames was investigated. Fig. 4 shows a photograph of the flame contact that occurred 0.01 s after the ignition with the initial pressure of 1.0 MPa. Fig. 5 shows a temporal change of the pressure in the chamber for 0.1 s after the ignition. Fig. 4 indicates that the flame brightness is higher in the center of the chamber where the flames contact each other than in the other areas. This is because the flame luminescence is accumulated over the distance in the depth direction as the flame shape changes to a plane. Fig. 5 indicates that the pressure at the moment of the flame contact is almost the same as the initial pressure. This feature remained under different pressure conditions.

### 4. Experimental results and discussions

#### 4.1 Shape of propagating flames

Figure 6 shows images of the propagating propane air premixture for different pressures. Even with increase of the initial pressure, the flame front was not disturbed by instability of the flames, indicating that the flame front became flat as the flames approached each other.

For calculation of the burning velocity with the double kernel method, it is necessary to calculate the distance between the front ends of the flames approaching each other. In the present study, the Schlieren images that we took were used to determine the boundaries of black areas approaching each other and define them as front ends of flames in order to calculate the flame separation. Fig. 7 shows the flame separation with the initial pressure of 0.1 MPa and photographs of the flames. As time passes, the flame separation reduces and the speed of the reduction decreases slowly.
The calculation method of the laminar flame speed based on this relation is described below.

4.2 Study of calculation method
4.2.1 Characteristics of temporal flame separation history

Figure 8 shows the relation between the flame separation and the flame propagation speed, which is the speed for the flames approaching each other, with the initial pressure of 0.1 MPa. It also shows photographs of propagating flames. For the calculation of the flame propagation speed, we used the second order central difference. The figure shows that the flame propagation speed decreases as time passes, namely as the flames approach each other. This is because, by the double kernel principle, a stagnation point appearing between the flames when the two flames approach each other reduces the expansion speed of the unburned premixture and the flame propagation speed becomes equal to the laminar flame speed. However, the flame propagation speed has three characteristic stages depending on the flame separation. The first is Stage (1) where the propagation velocity is almost constant or decreases slightly with the flame separation being about 8 mm or longer. The second is Stage (2) where the propagation velocity decreases rapidly and the deceleration rate is almost constant with the flame separation being from about 8 mm to about 2 mm. In this stage, the flame front is affected by the flow and the expansion effect is suppressed. Furthermore, when the flame front approaches the stagnation point, the effect of expansion is canceled, the deceleration speed of the flame propagation speed decreases, and the propagation speed converges to the constant value of the laminar flame speed. This area is
Fig. 8 Flame separation and flame propagation speed ($\phi=1.0$, $P_0=0.1$ MPa, $T_0=298$ K)

called Stage (3).

Raezer et al. and Yamazaki et al. examined the flame separation and the order of polynomials to use for a polynomial approximation and calculated the laminar flame speed. For example, if a temporal change of the flame separation is approximated with a quadratic form, the flame propagation speed is expressed as a linear function of time. Therefore, the flame separation is expressed as a quadratic function of the flame propagation speed. From the characteristics of Fig. 8, the quadratic form can be used to approximate Stages (1) and (2). However, Stage (3) has a different feature and the calculated laminar flame speed is expected to take a slightly smaller value.

On the other hand, Andrews et al. calculated the laminar flame speed by linear approximation of the temporal change of the flame separation immediately before the contact of the flames. Use of the linear approximation makes the flame propagation velocity constant and independent on the flame separation. Since the flame propagation speed turns to increase when the flame separation reaches a certain value, it is necessary, if this method is used, to accurately measure the region where the flame propagation speed decreases most. However, high precision adjustment of the moment when the flames contact each other is extremely difficult. The flame propagation velocity changes to increase because the preheat zones of the flames affect each other.

From the characteristics of Stage (3) in Fig. 8, one can consider that the stage can be approximated with an exponential function. Therefore, in the present study, we approximate the temporal change of the flame separation with a logarithmic function and use the resulting function to derive the relation between the flame separation and the flame propagation speed. We then extrapolate the flame propagation speed for the flame separation of 0 mm, namely for the moment when the flames contact each other, and obtain the laminar flame speed.

4.2.2 Study of effective flame separation for calculation of laminar flame speed

The flame propagation speed increases as the flames approach each other. The approximation is difficult when the flames stay apart. Then, we studied the flame separation effective for calculation of the laminar flame speed.

When two flames come closer, each one would receive influence from the preheat zone of the other. Therefore, we use thermal property values obtained from the numerical calculation of Chemkin Pro to calculate the preheat zone thickness. The results obtained for the case where the flame separation immediately before the flames contact each other is smaller than the preheat zone thickness are not used for calculation of the laminar flame speed. Therefore, the lower limit of the flame separation used for the calculation is set to the preheat zone thickness. The preheat zone thickness $\delta$ can be calculated from the following formula.

$$\delta = \frac{\lambda}{c_p \cdot \rho_u \cdot S_L} \tag{1}$$
Here, $c_p$ and $\lambda$ are the specific heat at constant pressure and thermal conductivity of the premixture, respectively. The preheat zone thickness for different initial pressures is shown in Fig. 9. The preheat zone thickness decreases with increase of the initial pressure. In this study, for the pressure of 0.1 MPa with which the preheat zone thickness reaches maximum, the Schlieren photographs show that the preheat zones overlap with each other or affect each other immediately before the two flames contact each other, namely when the flame separation is about 1 mm.

Fig. 9 Pressure dependence of preheat zone thickness

Fig. 10 Dependence of flame separation on calculation of laminar flame speed
Next, the upper limit of the flame separation for using analysis is examined. Since we need to take account of the preheat zone thickness, the upper limit of the flame separation was chosen to be 3-9 mm with an initial pressure of 0.1 MPa. For different initial pressures, the influence of the upper limit of the flame separation on the laminar flame speed is shown in Fig. 10. In each figure, the results obtained by using three sets of experimental data under the same initial pressure show. The figure shows that, as the flame separation used for the calculation becomes smaller, the calculated laminar flame speed increases. This tendency is significant when the initial pressure is as low as 0.1 MPa, although the speed maintains almost constant values when the flame separation is about 4 mm or smaller. Therefore, we set the upper limit of the flame separation used in the study to be 4 mm.

From the above, a flame separation equal to or less than 4 mm and larger than the preheat zone thickness is used. Therefore, four or five data points can be used for the approximation. In this study, we use four data points for the analysis.

### 4.2.3. Calculation of laminar flame speed

Figure 11 shows the laminar flame speed calculated with the method that the present study examined for different initial pressures. Experiments were conducted three times for each initial pressure condition and the results are plotted in the figure. In addition, the results of past studies are also plotted. The calculated laminar flame speed was almost the same as those of the past other reports.

### 5. Conclusion

In this study, the measuring system for laminar flame speed using simple compact equipment with the double kernel method using laser induced plasma as the ignition source was developed. The experiment was conducted on propane/air premixture so that it could be easily compared with the other reports. For the measurement, we used the propane/air premixture with the equivalent ratio of 1.0, room temperature of 298 K, and initial pressure up to 1.0 MPa. A detailed investigation of the time history of the flame separation revealed that the conventional method of calculating the laminar flame speed used in the double kernel method was not suitable for this measuring system. Therefore, a new laminar flame speed calculation method of logarithmic approximation of the separation was studied, and the pressure dependence of the laminar flame speed of the propane/air premixture was investigated. As a result, it was found to be almost consistent with other reports. However the approximation method using the exponential function used in this paper is based on the characteristics of stages 2 and 3, and has no physical meaning. In the future, it is considered that the accuracy can be further improved by studying the effect of expansion such as measuring the velocity between flame fronts.
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