30 Fractal Analysis of Flame Front during the Early Stages of Propagation in a SI Engine

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The objective of this study is to investigate the structure and characteristics of premixed turbulent flames in SI engines for the validation and improvement of the numerical simulation. Fractal analysis with LIF technique was performed to the flame of early stages in the cylinder and following results were obtained.

1) During the propagation, fractal dimension and inner cutoff were almost constant. Only outer cutoff scale was increased with flame radius. Therefore it seems that the increase of flame surface area is controlled by the flame own radius.

2) The flame surface area and laminar flame speed were obtained from the fractal measurements and compared to those of conventional combustion model. Fairly good agreements were obtained.

***Keywords* : Engine, Turbulent Flame, Burning Velocity, Numerical Simulation, Fractal Analysis**

1. INTRODUCTION

For further improvement of the fuel economy and performance of SI engine, especially for direct injection gasoline engines, it is necessary to investigate and optimize the combustion process. CFD simulation is most powerful tool for this purpose. The direct numerical simulation is still difficult for the practical engine analysis, therefore, development of combustion model is required. There were already many papers concerning combustion modeling of SI engines [(1)~(3)]. We also developed a combustion model based a flamelet concept [(1)] and applied it for the analysis of combustion process of a fan-shaped spray direct injection gasoline engine [(4)]. It was reported that the calculated combustion processes with the models were fairly in good agreement with experiments, however, further improvements were also required [(5)(6)].

On the other hand, the detail of flame structure in the SI engines is still not clear and it seems that it limits the improvement of combustion models. For example, it is well known that flame speed increases during the early stages of propagation. The flame speed is greatly different from that of fully developed steady flame. However, the mechanism is not clear, therefore, different types of combustion models are used in the stages.

From such a point of view, in this study, we performed the fractal analysis [(7)(8)] of flame front during early stages after ignition with LIF technique. Combustion characteristics, such as turbulent flame surface area and laminar flame speed were estimated from the fractal measurements and compared to those of combustion models.

2. FLAME CHARCTERISTICS AND FRACTAL

The flame structure in the cylinder of SI engines is considered as a wrinkled laminar flame. The heat release rate is controlled by both of the laminar flame speed S_L and total turbulent flame surface area A_T, as follows.

$$\dot{Q} = -q \cdot \dot{m}_f = -q \cdot Y_f \cdot \rho_u \cdot S_L \cdot A_T \qquad (1)$$

In previous studies, the validation of combustion model was mainly carried out by the heat release rate obtained from the in-cylinder pressure histories. In this study, we try the individual validation of the area and flame speed using fractal analysis. Turbulent flame speed S_T of spherical flame of mean radius R is usually represented as following equation.

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} = \frac{A_T}{4\pi R^2} = \left(\frac{\varepsilon_o}{\varepsilon_i}\right)^{D-2} \qquad (2)$$

D is fractal dimension, ε_o and ε_i are outer and inner cutoff scale corresponds to the maximum and minimum flame wrinkling size respectively. From the fractal measurements and equation (2), flame surface area can be obtained.

In early stages of flame propagation, the pressure change is almost negligible. Spherical flame propagation speed can be calculated from turbulent flame speed and expansion ratio by combustion.

$$\frac{dR}{dt} = S_T \cdot \left(\frac{\rho_u}{\rho_b}\right) = S_L \cdot \left(\frac{\varepsilon_o}{\varepsilon_i}\right)^{D-2} \left(\frac{\rho_u}{\rho_b}\right) \qquad (3)$$

The laminar flame speed can be estimated from both of fractal measurements and flame propagation speed from this equation.

3. EXPERIMENT

3.1. METHOD

A visualization engine was used for the measurement of LIF images. A laser sheet was introduced into the cylinder from the side of the engine. LIF lights of the fuel were measured from the bottom of cylinder. Figure 1 shows an example of the images. Clear frame front edge line was obtained. Figure 2 shows the fractal analysis method. Circle method was used for the fractal analysis.

Table 1 shows the outline of specifications and operating conditions. Fuel was premixed and supplied to the cylinder, but air fuel ratio was widely changed to simulate the stratified charge combustion conditions.

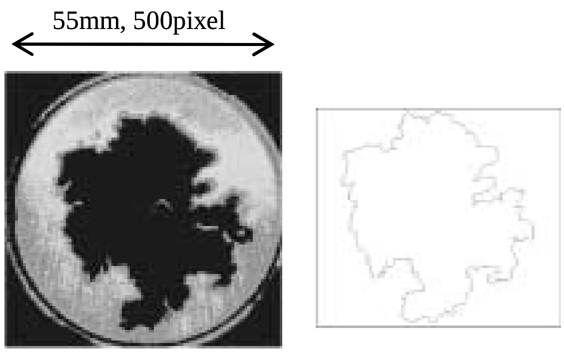


Fig.1. Example of flame front image obtained by LIF.

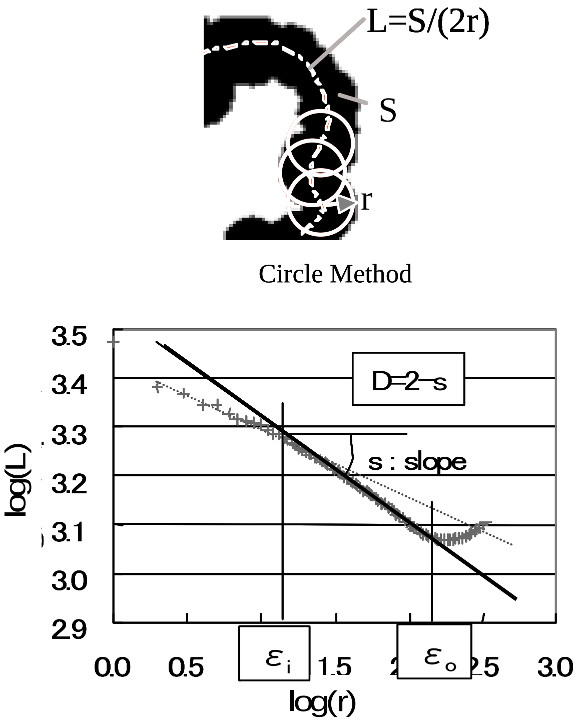


Fig.2. Fractal dimension and cutoff scale definition from circle method.

Table 1. Engine specifications and experimental conditions

Bore,Piston	86mm×86mm
Compression Ratio	9
Fuel	i-Octane
Speed	650, 1200 rpm
Load	50%
A/F	11 to 19

3.2 RESULTS

FRACTAL DIMENSION – Figure 3 shows the fractal dimension as a function of mean flame radius.
It seems that fractal dimension is almost constant during the early stages of propagation at each condition. This result means that the structure of flame wrinkling does not change during propagation.

Figure 4 shows the mean value at each condition. Fractal dimension increases with engine speed and effect of equivalence ratio is small.

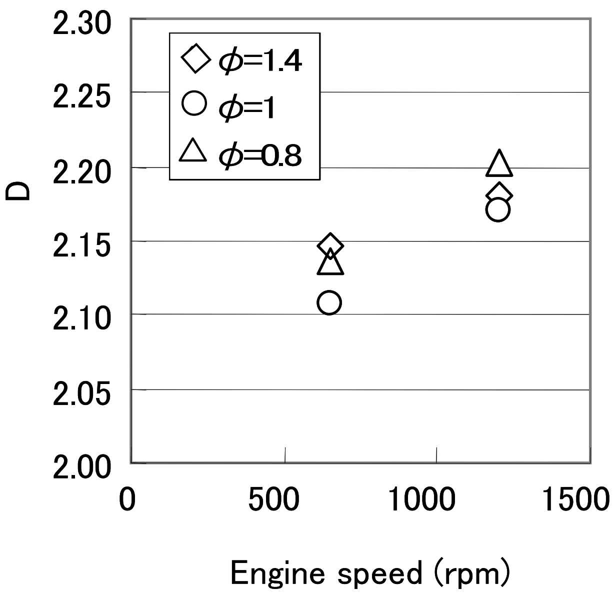
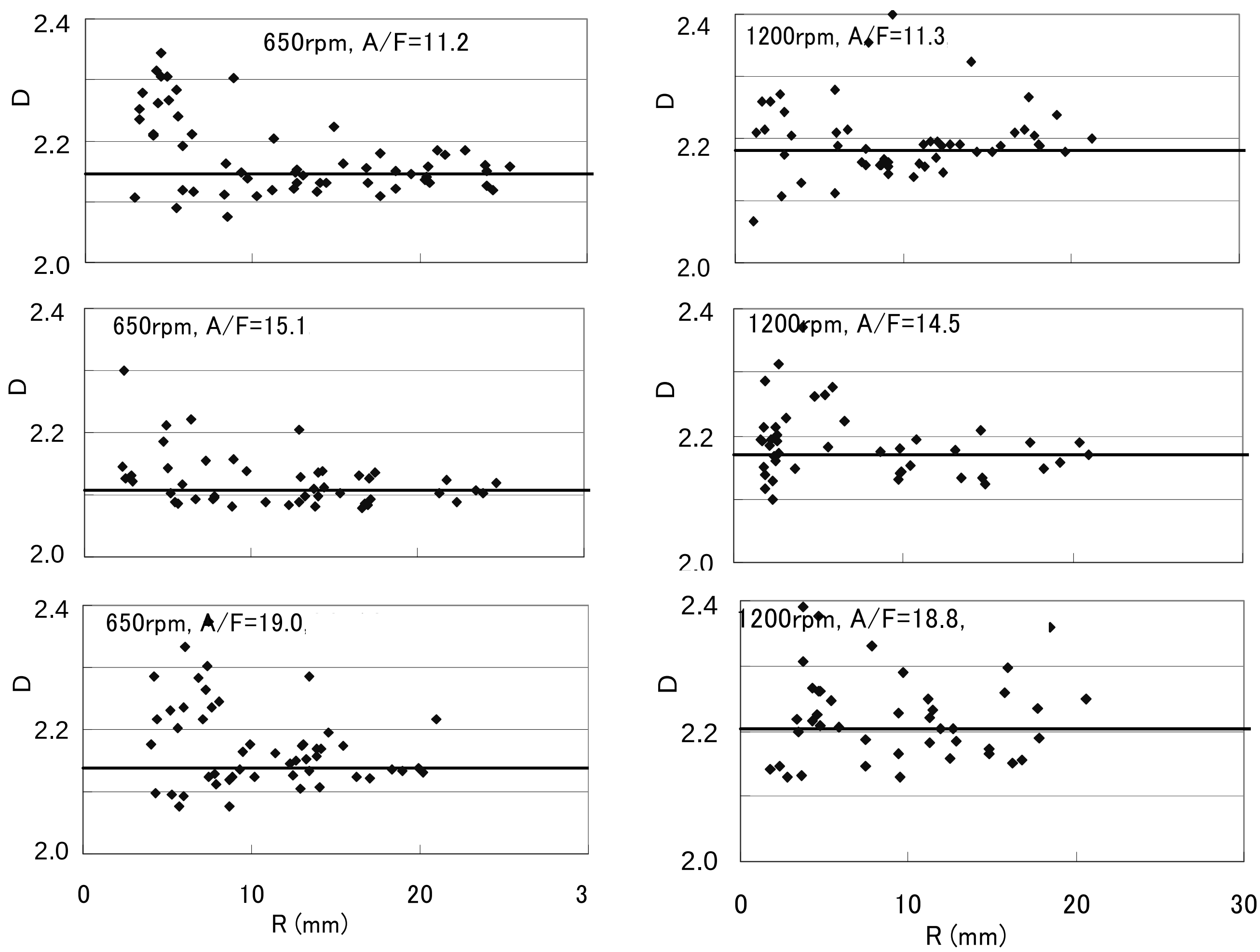


Fig.4. Mean fractal dimension during early stage.



(a)650rpm (b)1200rpm

Fig.3. Effect of air fuel ratio and engine speed on fractal dimension D. (R: mean flame radius)

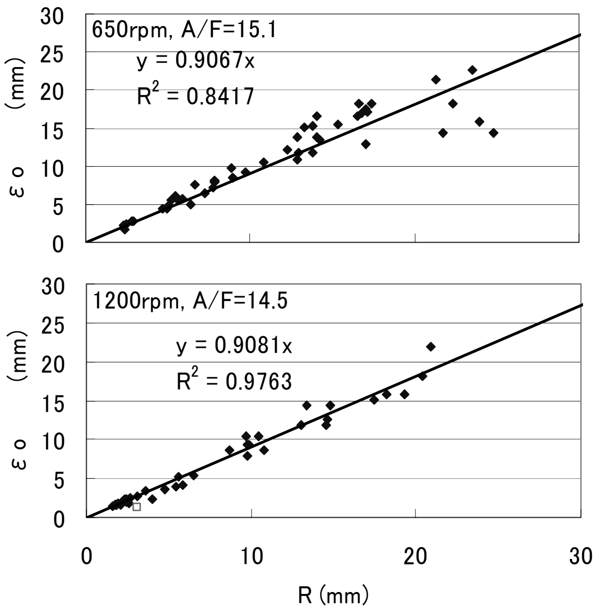


Fig.5. Outer cutoff scale as a function of mean flame radius.

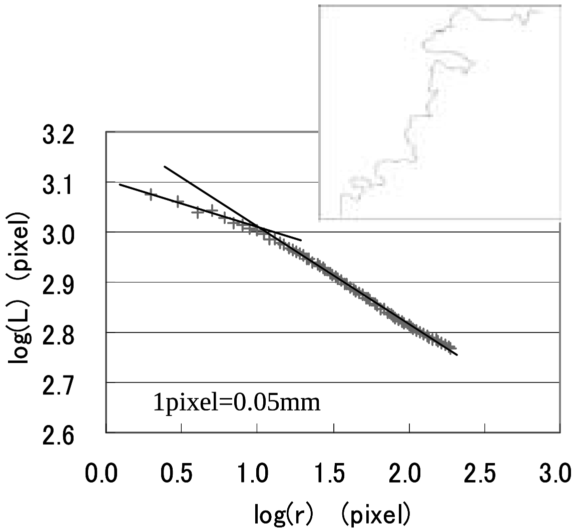


Fig.6 Sample of inner cutoff measurement.

CAUTOFF SCALES – Figure 5 shows the outer cutoff scale. The outer cutoff scale is almost same to flame mean radius. Figure 6 shows the sample of inner cutoff scale. Inner cutoff scale was almost constant in the conditions of this study and the value was approximately 0.8mm.

FLAME SURFACE AREA – Figure 7 shows the turbulent flame surface area calculated by equation (2). The flame surface area just after ignition is almost same to that of the laminar flame and rapidly increases. From the figure 5, outer cutoff scale is almost equal to flame radius, therefore, equation (2) can be rewritten as follows.

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} = C \cdot R^{D-2} \qquad (4)$$

The data from this equation is also plotted in figure 7. The tendency of increase of flame surface area is well estimated by this equation. From this results, it is considered that the increase of flame surface area during early stages is mainly controlled by large scale of turbulent and small eddies do not play any important role. This mechanism should be considered for the improvement of the flame propagation models.

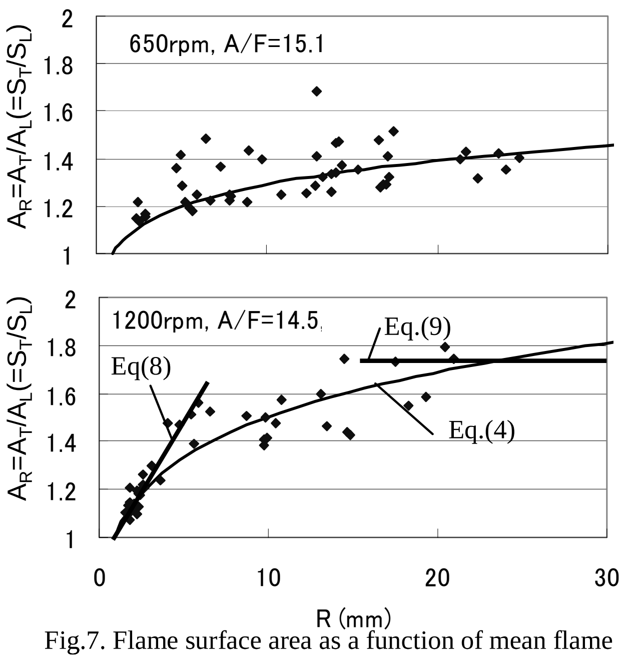


Fig.7. Flame surface area as a function of mean flame radius.

LAMINAR FLAME SPEED - Combining equation (3) and (4) yields the flame propagation speed as follows.

$$\frac{dR}{dt} = S_T \cdot \left(\frac{\rho_u}{\rho_b}\right) = C \cdot S_L \cdot R^{D-2}\left(\frac{\rho_u}{\rho_b}\right) \qquad (5)$$

If laminar flame speed is constant, equation (5) can be integrated and following equation is obtained.

$$R = \left\{S_L \cdot (-D+3) \cdot \left(\frac{\rho_u}{\rho_b}\right) \cdot C \cdot (t - t_0)\right\}^{\frac{1}{-D+3}} \qquad (6)$$

The unknown parameters in equation (6) are only laminar flame speed S_L and delay time t_0. These values were determined from flame propagation data using least square method. Figure 8 shows the example of the results. It shows that the good approximation is obtained and the laminar flame speed can be evaluated from this method.

Figure 9 shows the calculated laminar flame speed. The data of combustion models are also plotted in the figure. Relatively higher flame speed is observed in rich mixture conditions. It seems that the preferential diffusion affects to the flame speed and its modeling is very important. The detail of the models is discussed in the following section.

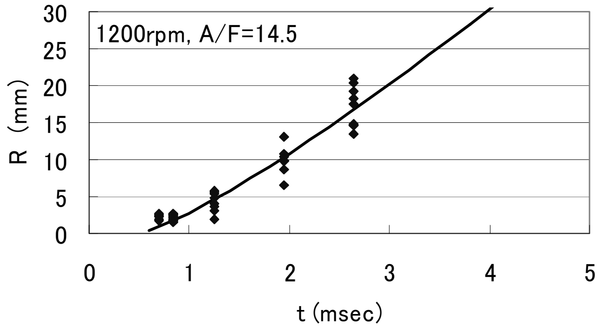


Fig.8. Time history of mean flame radius.

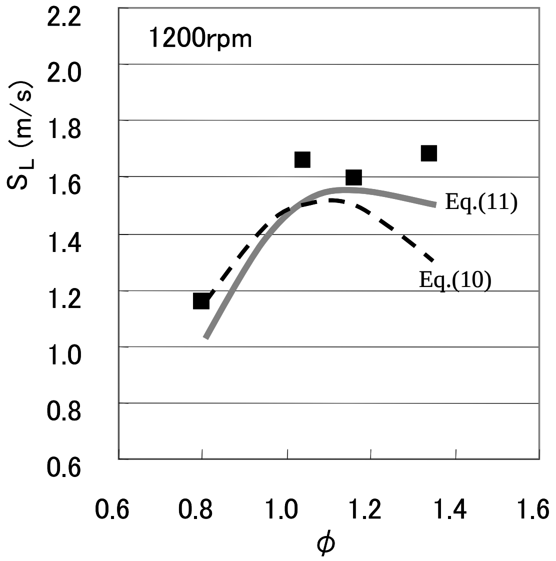


Fig.9. Estimated mean laminar flame speed.

4. VALIDATION OF COMBUSTION MODELS

4.1 FLAME SURFACE AREA

The CFM [(1)] (Coherent Flame Model) is often used for SI engine combustion calculation. We also use the similar model based the CFM. In this model, the following transport equation of turbulent flame surface density (flame surface area per unit volume) Σ is solved.

$$\frac{\partial \Sigma}{\partial t} + \frac{\partial u \Sigma}{\partial x} - \frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma}\frac{\partial \Sigma}{\partial x}\right) = K_L \Sigma + K_T \Sigma - D \qquad (7)$$

$$K_T = \alpha \cdot \Gamma \cdot \left(\frac{\varepsilon}{k}\right)$$

$$\Gamma = fn(u'/S_L, L_E/\ell_f)$$

K_L and K_T are thermal expansion and turbulent flame stretch respectively. K_T is computed by the ITNFS [(1)] model as a function of the relative turbulent intensity and length scale. α is a model constant and the suggested value is around 2. One of the advantages of this model is considered that it can be applicable for both of initial flame propagation and fully developed turbulent flames.

For the essential evaluation of the feature of this model, an analytical approach without solving the transported equation is carried out in this study. For initial flame propagation, the total surface area of entire flame is obtained by directly solving a simplified version of equation (7). Assuming spherical flame and ignoring the consumption term D, the following equation is obtained for initial flame propagation[(9)].

$$\frac{dA_T}{dt} = \frac{d}{dt}\left(4\pi R^2\right) + K_T \cdot A_T \qquad (8)$$

On the other hand, the turbulent flame speed of fully developed flame is obtained from KPP analysis of equation (7). Though the equation is affected by the formulation of consumption term, most common formulation is the following equation.

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} = \left(\frac{6\alpha\Gamma C_\mu}{\sigma_\Gamma}\right)^{\frac{1}{2}} \cdot \frac{u'}{S_L} \qquad (9)$$

The calculated flame surface areas from these equations are plotted in figure 7. 3-D CFD simulation results with k-ε turbulence model at ignition timing were used as turbulent characteristics in the cylinder. Good agreements are obtained for initial flame growth and saturated flame speed. It is confirmed that this model is applicable for any stages of flame propagation in SI engines.

4.2 LAMINAR FLAME SPEED

A laminar flame speed model proposed by Miyagawa etal[(6)] has been shown to be accurate at the wide range of mixture conditions. It is based the consideration of a mean reaction temperature as follows.

$$S_{L0} = Ap^{\gamma} \exp\left(-\frac{E}{2RT_r}\right) \qquad (10)$$
$$T_r = T_u + c(T_b - T_u)$$

T_r is defined as a mean temperature of adiabatic burnt gas and unburnt gas temperatures. Though this model contains no parameter directly related to the fuel concentration, but the effect of mixture conditions, such as equivalence ratio and amount of residual gases, is evaluated through the change of the burnt gas temperature.
The effect of flame stretching is also considered in the model as follows.

$$\frac{S_L}{S_{L0}} = 1 - Ma \cdot Ka \qquad (11)$$

Ka is Karlovitz number which represents the degree of stretching and Ma is Markstein number. It was shown that the Ma changes from positive to negative value in rich mixture conditions and it results in increase of laminar flame speed.
The calculated laminar flame speed is shown in figure 9. Fairly good agreement is obtained with the consideration of stretching effect.

Consequently, it is confirmed that the measurement of the detail of flame structure, individual validation of surface area and flame speed are very important for further improvements of combustion modeling. The improved models are used for the development of new SI combustion systems.

5. CONCLUSION

Fractal analysis with LIF technique was performed to the flame of early stages in the propagation. Following results were obtained.
1) During the propagation, fractal dimension and inner cutoff scale were almost constant. Only outer cutoff scale was increased with flame radius. Therefore, it seems that the growth of the flame is controlled by the large scale of turbulence.
2) Laminar flame speed in the real engine in-cylinder conditions was obtained from the fractal measurements. Relatively higher speed was observed in rich mixture conditions. It is confirmed that preferential diffusion effects is very important and it should be considered in engine combustion models.
3) Individual validation of flame surface area and laminar flame speed of combustion models was carried out. With the consideration of stretching effects, fairly good agreements were obtained.

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