Analysis of the fuel adhering to a model engine cylinder by using time series LIF methods

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Abstract

The purpose of this research is to determine an absolute measurement of the thickness of adhered fuel and amount of fuel spray in a model engine. To improve the accuracy of thickness measurements, use of the ratio of fluorescence intensities is proposed. An improved LIF (Laser Induced Fluorescence) method which uses the ratio of fluorescence intensity I/I_{ref} (I: fluorescence intensity, I_{ref}: fluorescence intensity of the fluorescent plate), is proposed and measurements were attempted. This technique can correct the influence of unequal light source intensity distribution. The proposed LIF method with high speed video camera was applied to measure the fuel adhesion thickness in a model engine cylinder. Each frame of the video images was successfully converted to a fuel thickness distribution. As a result, the behavior of fuel adhesion was evaluated by the proposed method. The adhered fuel thickness distribution and the amount due to the difference in injection conditions are presented in time series.

Introduction

In a gasoline engine, the adhesion of gasoline droplets to the wall is an undesirable phenomenon that causes unburned HC and oil dilution [1][2]. Analysis of the behavior of fuel adhesion is important since it can lead to a decrease in unburned gases and lesser particulate matter exhausted from an engine. The fiber LIF method was commonly used for thickness measurement of fuel adhering to a port or a cylinder wall. Johnen and Hang [3] measured the thickness of fuel adhesion to the wall using a fiber LIF method that combined the LIF method with an optical fiber. Takahashi et al. [4] measured the thickness of adhesion fuel to the wall in the suction port and in the cylinder by an improved fiber LIF method that a used single fiber. Iida et al. [5] carried out point measurements of the thickness of fuel adhering to a wall in time series using an LIF method. As the fiber LIF method is a point measurement, it is insufficient for evaluating the distribution and behavior of adhering fuel. On the other hand, the measurement of the amount of fuel adhering to a wall was tested by Yaoko et al. [6]. They measured the amount of adhered fuel using an electronic balance. The experiment was successfully carried out. However the results were obtained on a flat plate test piece. Thus, the application of this method in an actual engine cylinder would be difficult.

In this study, the time-series thickness of adhered fuel was measured using a combination of the LIF method and a high-speed camera. To improve the thickness measurement accuracy of adhering fuel, a calibration method with a reference image is proposed. The obtained thickness is converted to the amount of fuel adhering in the cylinder. The time-series data of the thickness and amount of adhering fuel are discussed in connection with the experimental results.

Experiment principle and measurement techniques

The LIF method has been applied for measuring temperature, thin film thickness, concentration and so on using the changes of fluorescence lifetime and intensity [7][8]. An explanation of LIF is shown in Figure 1.

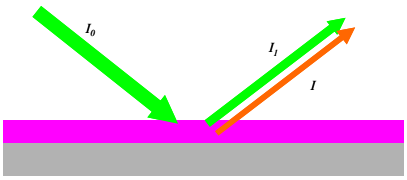

Figure1 LIF measurement

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In the figure, I_0 is the incident light intensity of the light source, I_1 is the intensity of the reflected light after passing the solvent with fluorescent material solution and I is fluorescence intensity.

The penetration of light in the solvent by the Beer-Lambert law is;

$$log_{10}(I_1/I_0) = -\varepsilon ct \quad (1)$$

$$I_1 = I_0 \cdot 10^{-\varepsilon ct} \quad (2)$$

where ε is the molar absorption coefficient, c is the molar concentration of a fluorescent material, t is thickness of the solvent. Fluorescence intensity I is shown as follows:

$$I = QI_a \quad (3)$$

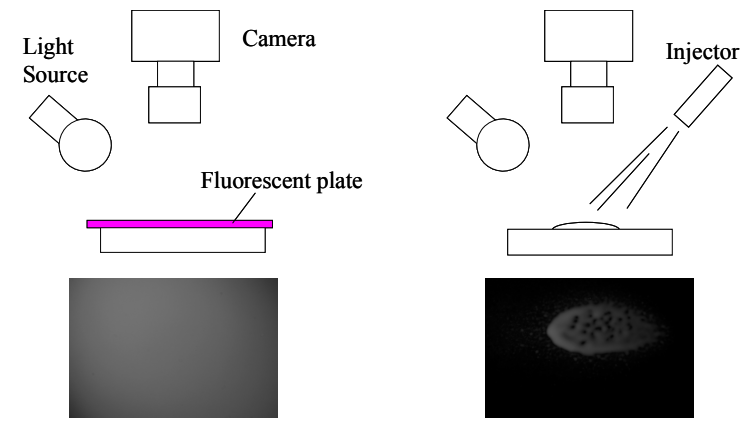
$$I = Q(I_0 - I_1) \quad (4)$$

$$I = Q\, I_0(1 - 10^{-\varepsilon ct}) \quad (5)$$

$$I = Q\, I_0\{1 - exp(-\varepsilon' ct)\} \qquad (\varepsilon' \fallingdotseq 2.303\varepsilon) \quad (6)$$

In the equations shown above, Q is the quantum efficiency of a fluorescent material, I_a is the intensity of the light absorbed in a fluorescent material solution.

This calculation is performed at all pixels in the image, and then the thickness distribution can be calculated. Since I_0 in the image is not uniform, it is necessary to correct the non-uniform distribution. In this research, a correction method using a fluorescent plate is proposed [9]. The fluorescence of the fluorescent plate I_{ref} is used as the standard fluorescence intensity. The fluorescence intensity of fuel I is divided by fluorescence intensity of the fluorescent plate I_{ref} in each pixel. The actual experimental method is shown in Figure 2. A fluorescent plate is installed on the part where fuel adheres, and the fluorescence intensity of the fluorescent plate I_{ref} is obtained. Then, the fluorescent plate is removed, and the fluorescence of fuel adhesion I is obtained. Figure 2(a), which is the result of the fluorescence intensity from the fluorescent plate, shows unevenness in the fluorescence intensity. This unevenness is due to the light source.



(a) Experimental apparatus for I_{ref} (a) Experimental apparatus for I

Figure 2 Experimental procedure

The fluorescence intensity of the fluorescent plate I_{ref} is treated as the penetration of light in the solvent, I_{ref} is expressed as:

$$I_{ref} = Q_f\, I_0\{1 - \exp(-\varepsilon_f' c_f t_f)\} \quad (7)$$

where Q_f, ε_f', c_f and t_f are the quantum efficiency, absorption coefficient, concentration, and thickness of the fluorescent plate, respectively. When the temperature change can be neglected, these variables are treated as constants. Then the fluorescence intensity of the fluorescent plate I_{ref} is shown as follows:

$$I_{ref} = A\, I_0 \tag{8}$$

$$A = Q_f\{1 - exp(-\varepsilon_f' c_f t_f)\} \tag{9}$$

Here, A is defined as the fluorescent plate constant. Thus, the ratio of fluorescence intensity I/I_{ref} is obtained from eqs. (6) and (8).

$$I/I_{ref} = Q\{1 - exp(-\varepsilon' ct)\}/A \tag{10}$$

Since the intensity of the source light I_0 is not in this expression, the unevenness of the light source can be disregarded. The dye solution is produced at a saturated condition. Then, concentration of fluorescent material to fuel, c, is treated as constant even if fuel evaporation occurs.

The relationship between fuel thickness and I/I_{ref} is obtained from the calibration experiment. The result of calibration experiment is expressed by a suitable function. The thickness at each pixel of the image is obtained by this function instead of eq.(10). The amount of fuel adhesion is calculated using the thickness, the pixel area, and the fuel density.

Preliminary experiment

In this method, the accuracy of the thickness distribution depends on the accuracy of the I_{ref}. Since the intensity distribution of I_{ref} is treated as the unevenness of the light source, the unevenness of the fluorescence dye, due to the layer thickness, scratch, and so on, on the plate causes errors in thickness measurement. The preliminary experiment for evaluating the fluorescence intensity distribution characteristics of the fluorescent plate used in this research is carried out to address this problem. The experimental apparatus is shown in Figure 3. The measuring object is a fluorescent plate. Ultraviolet rays from UVLED (Nichia Corporation NSPU510CS×92, emission peak wavelength: 375 nm) are irradiated to the object. The object is a fluorescent plate with a size of 260 × 260 mm. A high-speed camera (Phantom v710, picture resolution: 1280×800, frame speed: 1000 fps) takes images of the fluorescence. The actual image area is about 100 mm × 62.5 mm. A color filter (Kenko Y44) is installed in front of the lens, which removes light from the light source and leaves only the fluorescence pattern. After an image is taken, the fluorescent plate is moved in a random direction at a certain distance and then the image is taken again. Ten images were taken following the same procedure. An example of the images is shown in Figure 4. The intensity measurement points are represented by A (640, 200) and B (640, 600) in Fig.4. Data from ten different positions in the actual plate were recorded at each measurement point as shown in Table 1. The unevenness of the fluorescence of the fluorescent plate is about 5 in 3σ. This shows that the unevenness of the fluorescence intensity of the fluorescent plate is small enough to be negligible.

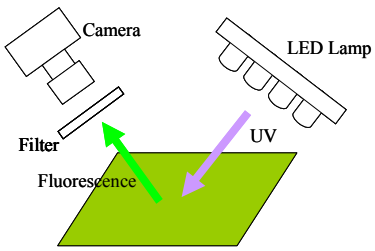


Figure 3 Experimental apparatus

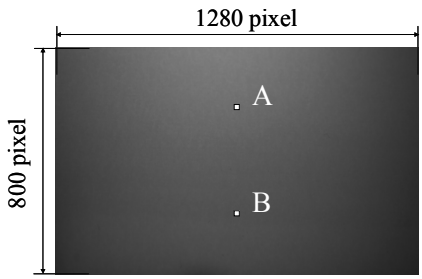


Figure 4 Measurement point

Table 1 Experimental results

		A	B
N	1	104	75
	2	100	74
	3	103	77
	4	105	77
	5	103	74
	6	105	74
	7	103	73
	8	100	72
	9	103	75
	10	103	75
average		102.9	74.6
σ		1.64	1.50
3σ		4.92	4.49

Calibration

To examine the relationship between the ratio of fluorescence intensity I/I_{ref} and the thickness t, a calibration test was carried out. Perylene ($C_{20}H_{12}$), which was used for the fluorescent dye, was dissolved by toluene, and mixed with n-heptane which is the main fuel for the spray. The concentration of perylene is 0.4 g/dm^3. This is the ratio of the concentration of saturated solution to fuel.

The experimental apparatus is shown in Figure 5. The calibration measurement object is shown in Figure 6. It consists of two slide glasses and feeler gauges which have known thicknesses. The light source, the high-speed camera and photography conditions are the same as mentioned in the previous section. 9 kinds of feeler gauges (0.01, 0.02, 0.05, 0.08, 0.10, 0.12, 0.15, 0.20 and 0.25mm) are used to make the calibrating object. These results represent I. The fluorescence of the fluorescent plate is taken at the same position. This result represents I_{ref}. The relationship between I/I_{ref} and the thickness of the fuel is obtained.

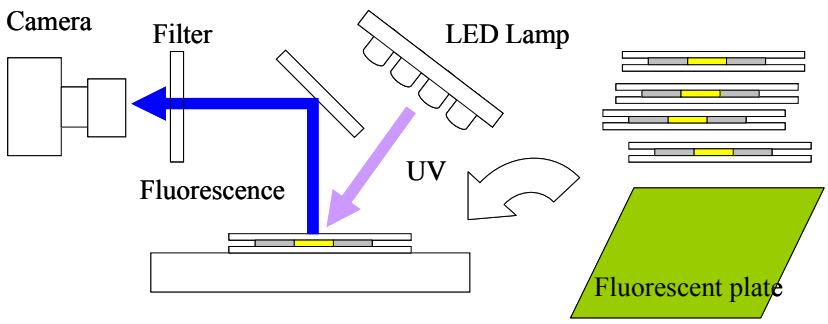


Figure 5 Experimental apparatus

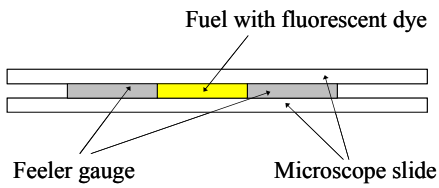


Figure 6 details of measurement object

The experimental result of the calibration experiment is shown in Figure 7. It is shown that the relationship between the thickness t and I/I_{ref} is a quadratic function. The ratio of fluorescence intensity I/I_{ref} and fuel thickness t is expressed as follows:

$$t = 0.228(I/I_{ref})^2 + 0.404(I/I_{ref}) \tag{11}$$

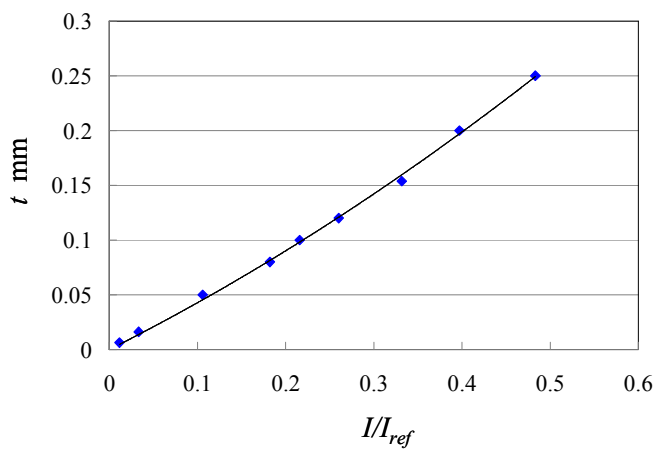


Figure 7 Experimental results of calibration

From the results of the preliminary experiment and the calibration test, the error in the thickness measurement is evaluated at a maximum of 7%. In order to reduce this error, more images of the fluorescent plate were taken to obtain accurate I_{ref}.

Measurement of fuel adhering to the surface of a cylinder wall in a model engine

Measurements of the fuel thickness and the amount of fuel adhering to the cylinder wall were conducted in a model engine. The experimental apparatus is shown in Figure 8 and the experimental conditions are shown in Table 2. Injection durations of 1.0, 1.5, and 2.0 ms were tested. The cylinder of the model engine used in this research is made of transparent plastic. The fuel adhering to the surface of a cylinder wall can be observed from outside of the model engine. All imaging conditions, i.e. the light source, the high-speed camera and so on, are the same as those of the preliminary experiment and the calibrating experiment.

In order to obtain I_{ref}, the fluorescent plate was attached to the inner wall of a cylinder. UV light was irradiated to it from a light source, and the fluorescence was taken by a high-speed camera. This work was carried out 3 times changing the position of the fluorescent plate each time. The intensities at all of the pixels were obtained by averaging the results. It is used in the I_{ref} distribution. The fluorescent plate was removed and the fuel was injected to the wall surface. The intensity distribution of the image of the adhered fuel I was divided by I_{ref} in the same pixel position. The I/I_{ref} distribution was converted into the thickness using eq.(11). The amount of adhered fuel was calculated by taking the product of the pixel area and fuel density.

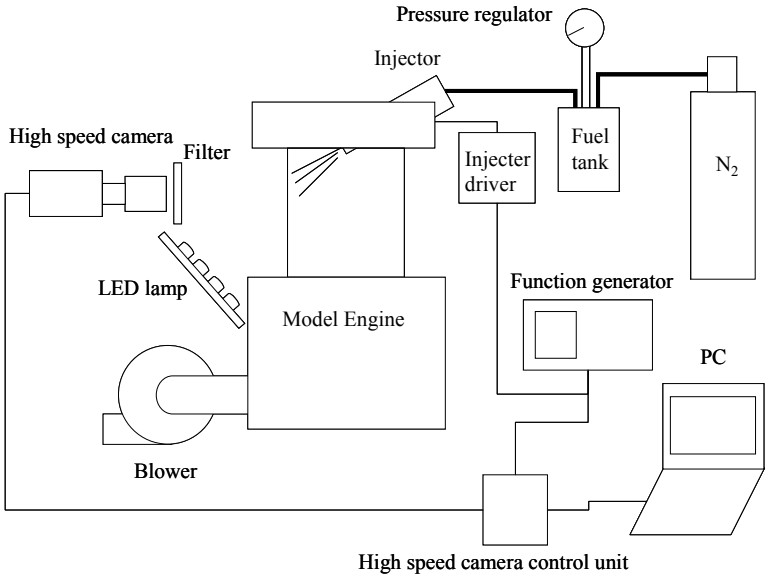


Figure 8 Experimental apparatus

Table 2 Experimental conditions

Bore	75mm
Fuel pressure	10MPa
Fuel Temperature	20℃
Room temperature	20℃

The thickness distribution maps for injection durations of 1.5 and 2.0 ms are shown in Figures 9 and 10, respectively. The cylinder position of the model engine is shown in the figures. The figures indicate the time-series thickness distributions of the adhered fuel after injection. The first frame which was when the spray tip reached the wall surface was set to 0 ms. The gray scale in the figures indicates the thickness distribution of adhered fuel. This can be obtained with the time-series data. The advantage of this experimental method is that it can provide a time-dependent thickness distribution of a certain area.

In the figures, some thick parts of adhered fuel can be observed. The fuel thickness at the outer edge of the spray impinging area is thicker than that at the center. The change in the thickness with time is recognizable until 7ms. For example, the thin adhered fuel can be observed between the main spray impinging areas at 4 ms. The fuel at these areas disappears or becomes thinner at 5 ms. This result is mainly caused by fuel evaporation. The change in the adhering fuel thickness becomes small after 7 ms.

Comparison between the injection durations of 1.5 and 2.0 ms shows the difference in the absolute thickness of the adhered fuel. The thickness at injection duration of 2.0 ms is thicker than that at 1.5ms. The patterns of adhered fuel are similar, however the fuel adhered area at injection duration of 2.0 ms is larger than that at 1.5 ms. These results are due to the large amount of injected fuel for the injection duration of 2.0ms.

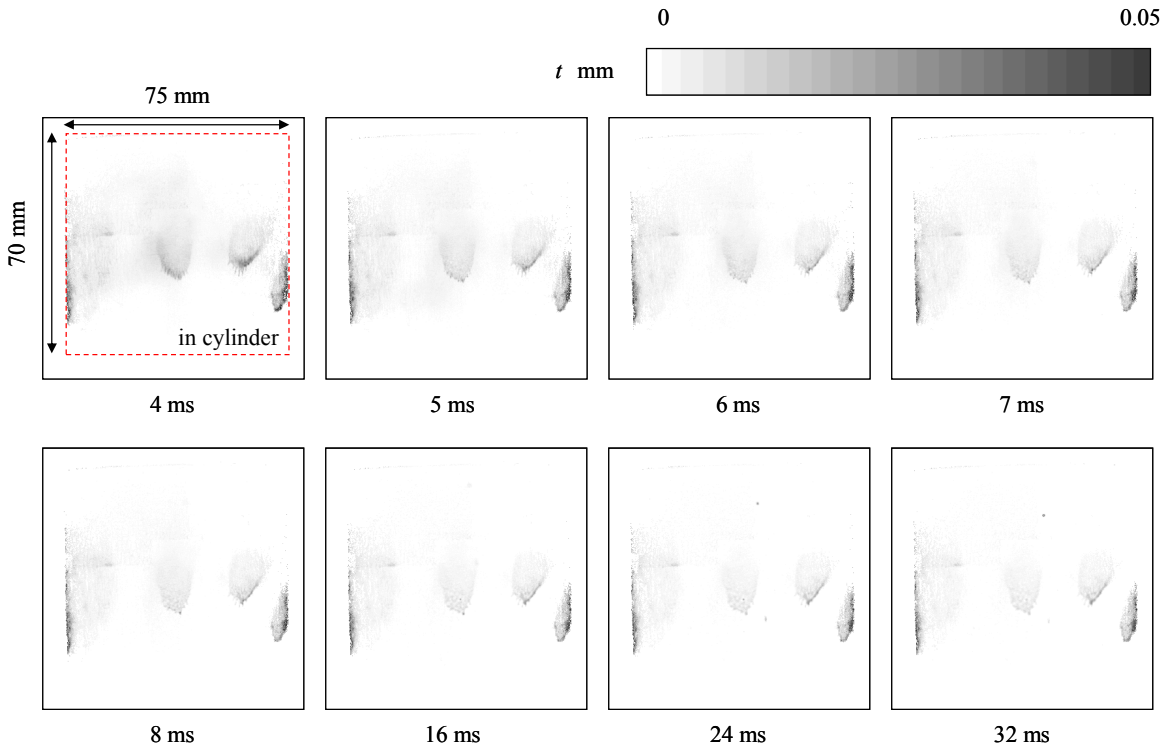


Figure 9 Fuel thickness distribution (injection duration: 1.5ms)

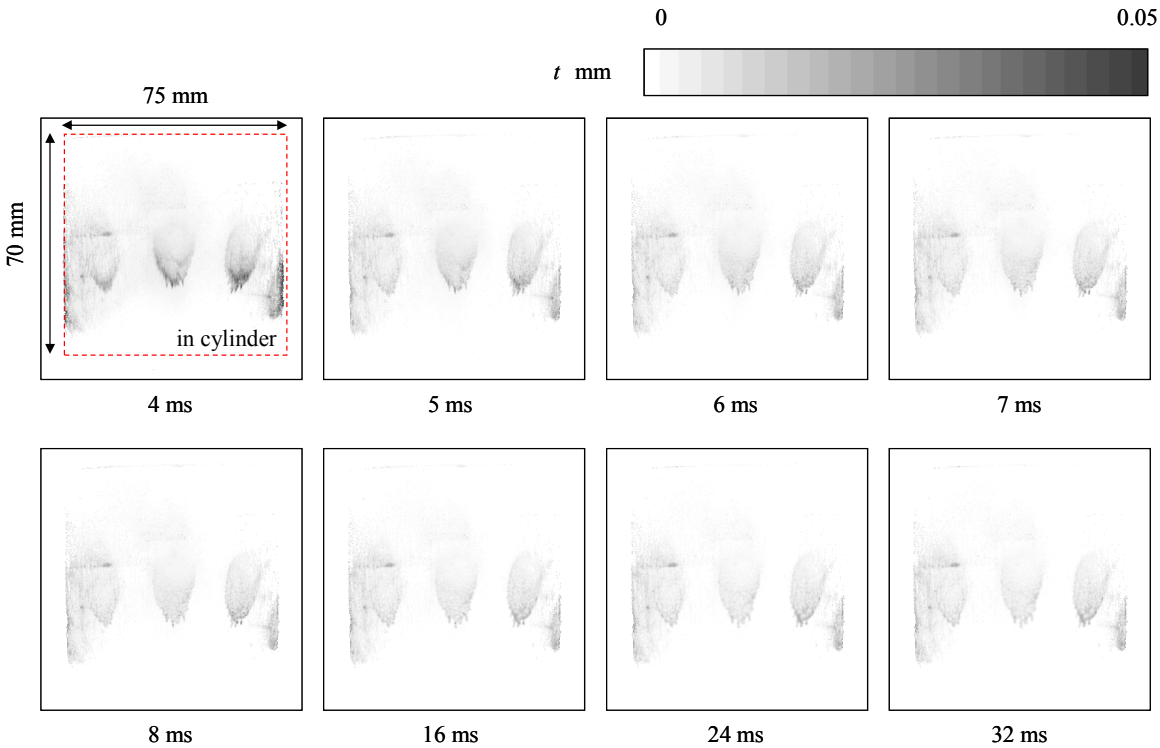


Figure 10 Fuel thickness distribution (injection duration: 2.0ms)

The amount of fuel adhering to the wall surface is shown in Figure 11. The vertical axis of the figure is the amount of fuel adhesion (g) and the horizontal axis is the time which is the same as that in Figures 9 and 10. The amount of adhered fuel rapidly decreased until 7 ms in all injection duration conditions. After 7 ms, the change in this amount becomes small. As mentioned before, the main reason for this decrease is fuel evaporation. After 7 ms, fuel evaporation ceases in this experiment.

The change in the adhesion area on the surface of a wall is shown in Figure 12. The vertical axis of the figure is the adhesion area (mm^2) and the horizontal axis is the time. The adhesion area decreases up to 7 ms as the amount of adhered fuel decreases. After 7 ms, the adhesion area continues to decrease. The results shown in both Figures 11 and 12 indicate that the amount of adhered fuel is hardly changed but the adhered area becomes smaller. This result suggests that after 7 ms the local fuel thickness increases with time.

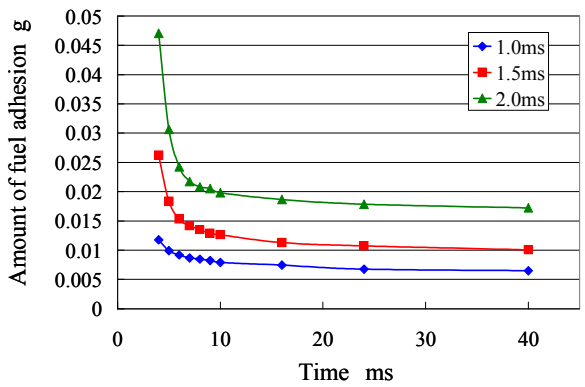


Figure 11 change of amount of fuel adhesion

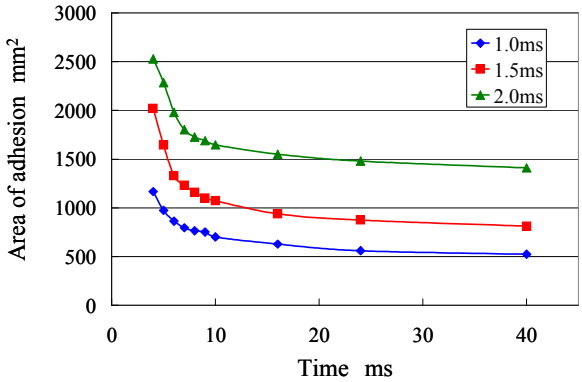


Figure 12 change of amount of adhesion area

In order to clarify the evaporation and the behavior of adhered fuel in detail, the change in thickness with time is shown in Figures 13 and 14. These figures summarize the frequency distribution of the thickness on the center line of the thickness distribution image of Figure 9. In these figures, the horizontal axis represents the thickness range and the vertical axis shows the number of pixels in each thickness range. Figure 13 shows the results before 10ms after injection, and Figure 14 shows the result of 10 to 40 ms after injection. At 4 ms after adhesion, the fuel thickness has two peaks as shown in Figure 13. The peak at the thickness range of 0.030 to 0.035mm decreases with time. On the other hand, the peak at the thickness range of 0.005 to 0.010mm becomes large. In this time range, evaporation is active. Since the amount of adhered fuel decreased by evaporation, the frequency of thinner adhered fuel increased. In Figure 14, the peak of the thickness ranges from 0.005 to 0.01mm. At this range, the number of pixel decreases with time. The frequency distribution increases in the thickness range of 0.02 to 0.04mm. In this time range, fuel evaporation is not active as shown in Figure 11. The fuel at the thickness range of 0.005 to 0.01mm seems to move toward the thickness range of 0.02 to 0.04. That is, the fuel accumulated forming a thick film. The accumulation of the adhered fuel is caused by the surface tension and the gravity.

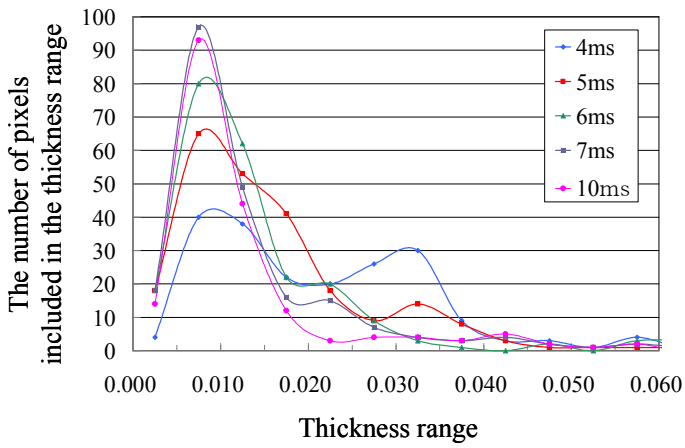


Figure 13 change of thickness range
(injection after 4 - 10ms)

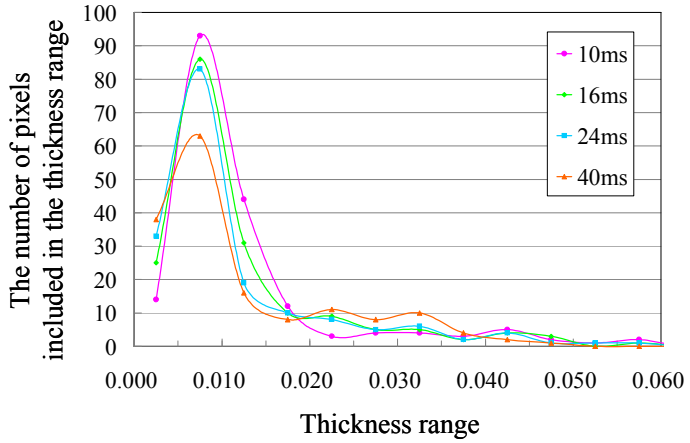


Figure 14 change of thickness range
(injection after 10 - 40ms)

Conclusions

In this research, a method to correct the light source unevenness in the LIF method using fluorescent plate. The fuel adhering to the cylinder wall of the model engine is measured by this improved LIF method. The main conclusions are as follows:

- Fuel evaporation on the wall surface can be evaluated using the proposed method. Evaporation is active before 7 ms after the fuel reaches the wall surface.

- The amount of adhered fuel becomes almost constant after 7 ms although the adhesion area decreased. The fuel film was affected by the surface tension and gravity.

- The behavior of adhered fuel is evaluated using the proposed LIF method.

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