Investigation of Soot Formation in a D.I. Diesel Engine by Using Laser Induced Scattering and Laser Induced Incandescence

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Soot has a great effect on the formation of PM (Particulate Matter) in D.I. (Direct Injection) Diesel engines. Soot in diesel flame is formed by incomplete combustion when the fuel atomization and mixture formation were poor. Therefore, the understanding of soot formation in a D.I. diesel engine is mandatory to reduce PM in exhaust gas. To investigate soot formation in diesel combustion, various measurements have been performed with laser diagnostics. In this study, the relative soot diameter and the relative number density in a D.I. engine was measured by using LIS (Laser Induced Scattering) and LII (Laser Induced Incandescence) methods simultaneously which are planar imaging techniques. And a visualization D.I. diesel engine was used to introduce a laser beam into the combustion chamber and investigate the diffusion flame characteristics. To find the optimal condition that reduces soot formation in diesel combustion, various injection timing and the swirl flow in the cylinder using the SCV (Swirl Control Valve) were applied. From this experiment, the effects of injection timing and swirl on soot formation were established. Effective reduction of soot formation is possible through the control of these two factors.

Key Words: Spray, LII (Laser Induced Incandescence), LIS (Laser Induced Scattering), D.I. Diesel Engine, Swirl, Soot Distribution, Visualization

Nomenclature

ATDC : After top dead center
BTDC : Before top dead center
D : Particle diameter
DI : Direct injection
Dr : Relative diameter
ICCD : Intensified charge coupled device
I_{LII} : Intensity of LII signal
Isca : Intensity of elastic scattering light
LII : Laser induced incandescence
LIS : Laser induced scattering
N : Number density
Nr : Relative number of density
PM : Particulate matter
SCV : Swirl control valve
TDC : Top dead center

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1. Introduction

In recent years the direct-injection (DI) diesel engine has became more and more popular due to excellent thermal efficiency and durability compared to other engine system. D.I. diesel engine contributes to minimize the green house gases because its low fuel consumption leads to low CO2 emission. However, it is still true that the major difficulty with the D.I. diesel engine is to control its emissions of nitrogen oxides (NOx) and particulate matter (PM), both of which are characteristic of the spray combustion process. Thus, many researches have been performed to improve the combustion and emission in a D.I. Diesel engine. (Dec, 1997) Especially, the reduction technology of soot formation in the combustion chamber is needed to meet the stringent of environmental regulations. (Wiltafsky et al., 1996) In order to reduce soot emissions, it is necessary to investigate how soot is formed during the combustion process. For these reasons, there have been several attempts to apply modern laser-based techniques to soot distribution measurement. (Loye et al., 1990 ; Hidenori et al., 1995) In this study, the optical measurement techniques such as LII (Laser Induced Incandescence) and LIS (Laser Induced Scattering) were established in order to visualize the distribution of soot. In addition, the algorithm for calculating relative diameter and density of particle (Lee et al., 2001) from the images measured by the LIS and LII was developed and applied to measure the distribution of soot and spray simultaneously in a D.I. diesel engine. From this experiment, existence of soot in the rich region of spray was found

2. Principals of LII and LIS

2.1 LIS

When the laser sheet passes through the diffusion flame, dispersion is occurred due to the droplet and soot that has a large diameter. The intensity of scattering is calculated by the equation (1).

$$I_{sca} \propto D^6 N \quad (1)$$

where, D is the particle diameter and N is the number density.

The two dimensional LIS signal is obtained from the elastic scattering light. This signal is stronger than those of LII and LIF signals. LIS signal can be separated from the elastic scattering signal by narrow band pass filter. In this experiment, LIF signal was eliminated by the narrow band pass filter and extremely short gate time.

However, since LIS signal is stronger than LII signal, the droplet signal is still contained in the LIS signal. When the LIS and LII experiment were conducted simultaneously, distribution of the large droplet and soot could be investigated.

2.2 LII

It is well known that the LII signal is generated by thermal radiation of soot. The abrupt increase of temperature of soot caused by laser sheet beam produces this thermal radiation. The ultraviolet optical filter, short wave pass filter and band pass filter were used to obtain LII signal. By using these filters, other signals could be eliminated. The intensity of LII signal (I_{LII}) is calculated by the following equation (2).

$$I_{LII} \propto D^3 N \quad (2)$$

The laser sheet beam passing through the spray is mainly used to heat soot particle. The heat transfer and thermal radiation to ambient gas can be disregarded. Therefore, soot temperature is only affected by the energy of laser sheet beam and soot could be vaporized by the sudden increase of the temperature.

The time scale of soot temperature rising is affected by the shape and temperature of laser. This is corresponded to the pulse width of the laser (Nd :Yag laser, 8-10 ns). It is well known that a sudden large thermal radiation occurred before soot vaporizing. This thermal radiation transfers to very short wavelength and the maximum value is relatively 10^3 higher than the thermal radiation of soot (2300 K).

2.3 Calculation of relative number density and diameter

The relative number density and diameter were calculated by using LII and LIS simultaneously.

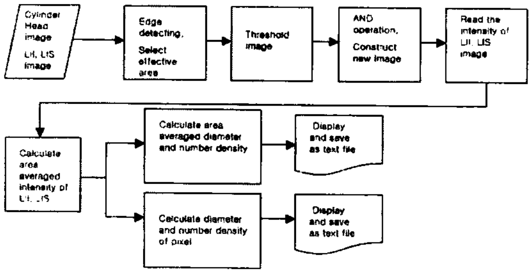


Fig. 1 Calculation procedure of relative diameter and density

From definitions, equation (1) and (2) can be translated to next equations.

$$I_{sca} \propto D^6 N \tag{3}$$

$$N \propto I_{LII}^2 / I_{sca} \tag{4}$$

$$D \propto (I_{SCA}/I_{LII})^{1/3} \tag{5}$$

The relative number density and diameter are calculated by the following equations.

$$Dr \equiv (I_{sca}/I_{LII})^{1/3} \tag{6}$$

$$Nr \equiv (I_{LII})^2 / I_{sca} \tag{7}$$

However, since the LIS signal has the droplet signal, these equations can be used in the special area, which has the LIS and LII signal simultaneously.

The cyclic variation was ignored in this calculation. Thus, the effect of cyclic variation was removed by using the relative luminance. The relative luminance was calculated by the equations (8) and (9).

$$\overline{I_{sca}} \equiv \Sigma[\overline{I_{sca}}(i) \cdot A_{sca}(i)] / \Sigma A_{sca}(i) \tag{8}$$

$$\overline{I_{LII}} \equiv \Sigma[\overline{I_{LII}}(i) \cdot A_{LII}(i)] / \Sigma A_{LII}(i) \tag{9}$$

In this equation, $I_{LII}(i)$ and Isca (i) mean the luminance (I=1-256) of calculated area. In addition, $A_{LII}(i)$ and $A_{sca}(i)$ mean the number of pixel. Figure 1 shows the flow chart of calculation.

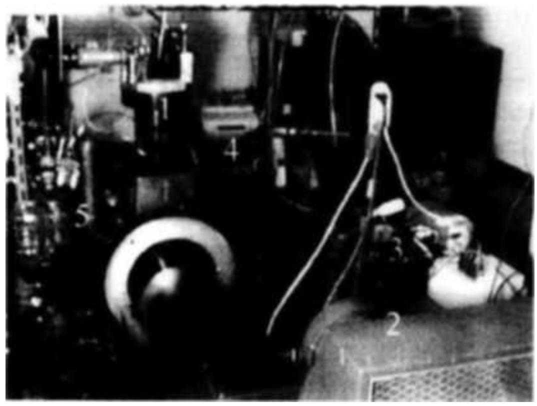
3. Experimental setup

3.1 Visualization engine system

In this study, a single cylinder D.I. diesel engine, which has the optical window and piston, was used. Figure 2 shows the visualization engine system. This engine system has the optical windows on the side of cylinder in order to input the laser sheet beam through the combustion chamber. In addition, the piston is replaced by using the transparent quartz piston to investigate the spray characteristics from the bottom view. This system is driven by DC Motor (22 kW) and

Table 1 Specification of D.I. Diesel Engine

Engine Type	Two Valve Type Single Cylinder. N.A.
Injection Type	Direct Injection
Compression Ratio	17
Displacement Volume	673 [cc]
Bore × Stroke	95×95 [mm]



1. Visualization engine 2. Driving motor
3. Amplifiers for signal 4. Injection Controller
5. Injection pump

Fig. 2 Configuration of the transparent D.I. diesel engine system

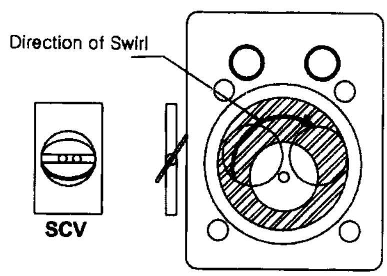


Fig. 3 Schematic diagram of SCV and direction of the swirl flow

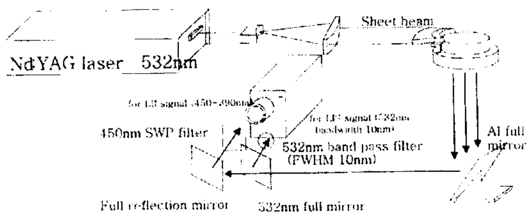


Fig. 4 Schematic diagram of optical setup

can change the injection timing by using the fuel control system (ZEXEL, Copec). A five-hole type injector was used in this study. Table 1 shows the specification of this engine system To intensify swirl flow, the SCV (Swirl Control Valve) was used. The SCV is installed in front of intake port. Figure 3 shows the shape of SCV and direction of the swirl flow.

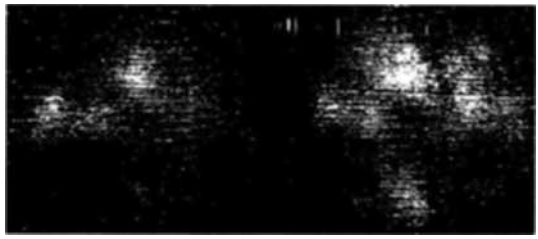
3.2 Optical setup for LIS and LII system

In this study, an optical setup for simultaneous LIS and LII experiments was developed. Generally, LIS and LII experiments are performed with two cameras. However, in this study only one ICCD camera (V-tek, MXIII-10N) was used to conduct LIS and LII experiment. For the LIS experiment, the 532 nm full reflection mirror and 532 nm narrow band pass filter (FWHM 10 nm) were used to obtain a LIS signal. The full reflection mirror and 450 nm short wave pass filter (FWHM 40 nm) were also used for LII experiment. Figure 4 shows the optical setup for LIS and LII system used in this experiment.

4. Experimental Results

4.1 Characteristics of soot distribution

In this study, the distribution of soot in diffusion flame was investigated by using the LIS and LII simultaneous experiment. The relative diameter and number density of soot are also obtained by calculating the equations (8) and (9). Figure 5 shows the original image which was taken by LIS and LII simultaneous experiment. The intensity of original image was strengthened using threshold because original images of LIS and LII signals were extremely weak. The LIS signal has the elastic scattering light from both droplet and



(a) LIS image (b) LII image

Fig. 5 Raw images of LIS and LII (5hole, TDC injection, ATDC 15CA image capture)

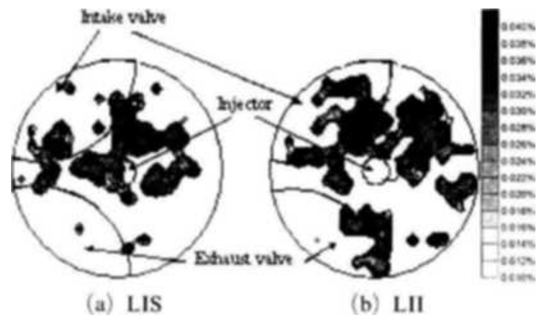


Fig. 6 Modified images of LIS and LII

soot. Therefore, the LIS signal is considered that only came from droplet signal.

As shown in Fig. 5, the LII signal was also existed in the large LIS signal area. Both signal were appeared near the spray, which injected from five-hole nozzle.

From this figure, we knew that the area, which shows strong intensity of LIS and LII, means the soot was developed more abundantly where incomplete combustion could be occurred due to the non-uniform air-fuel mixture formation. The image modification procedure was performed to analyze the distribution of intensity on local area. To modify the original image, noise from the original image was removed and filtered low signal below the special value of gray level. Finally, new image after finishing this process could be obtained. Figure 6 shows the modified image obtained by this process.

In this figure gray level 256 was defined as 100%. The value of proportional gray level is showed in the right side of figure. The distribution of proportional gray level is existed in the range from 0.01% to 0.04%. This means that the LIS and LII signals are extremely low. From this figure, it was found that inside of spray showed higher gray level than that of outside. This result revealed that the density of soot is high in this area where incomplete combustion could be occurred. This trend is caused by the fact that the air-fuel mixing in outside region is promoted faster than that of inside region because the outside of spray is easy to mix the air. Therefore, a rich fuel ratio is existed at the inside of spray.

Especially, the LIS and LII signals near the intake valve side are stronger than that of exhaust valve side. Because the temperature of intake side is lower than the exhaust side, the fuel existed near the intake side is difficult to evaporate compared to the exhaust side fuel. Therefore, the mixture formation of exhaust region is better than that of intake region. This good mixture condition resulted in reduction of soot distribution in the exhaust valve region.

Figure 7 and 8 show the relative number density and relative diameter distribution of soot, respectively. The calculation procedure is shown in Fig. 1. The results of these figures indicated soot distribution excluded droplet signal.

Similar to Fig. 6, the distribution of soot is concentrated at the inside of spray and intake valve side. These figures revealed that soot formation is developed along the shape of spray. In addition, the larger soot particle exists in the inside region of distributed area as shown in Fig. 8.

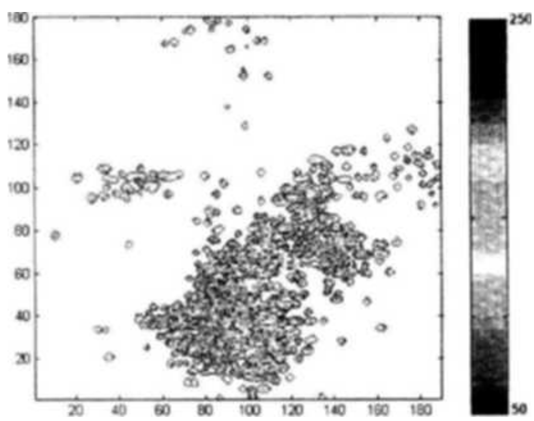


Fig. 7 Relative density distribution of soot

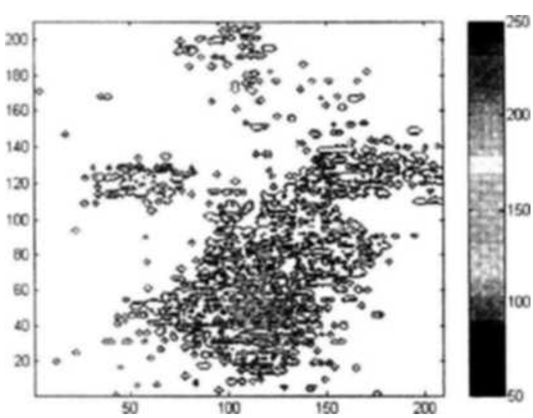


Fig. 8 Relative diameter distribution of soot

4.2 Distribution of soot with injection timing

The heat release rate with various injection timings was compared to analyze the effect of injection conditions (Dec, Espey, 1995). Three injection timings (12° BTDC, 8° BTDC, TDC) were chosen as the experimental conditions. Figure 9 shows the comparison of heat release rate between three cases. As the injection timing is retarded, the crank angle showed the maximum values of heat release appeared later than other timings. Especially, in the case of BTDC 8° injection condition, the maximum value of heat release is higher than other conditions.

In addition, the effective area ratio was calculated to analyze soot distribution quantitati-

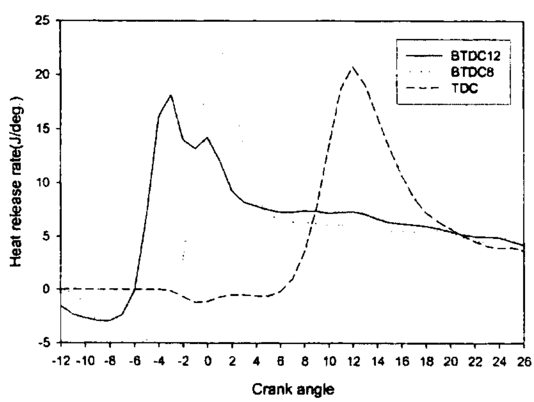


Fig. 9 Comparison of heat release rate (Injection : 12°, 8° BTDC, TDC, A/F=48, 400 rpm)

vely. The effective area ratio is defined as the ratio of the area contained LIS and LII signals to total horizontal cylinder area. Figure 10 and 11 show the effective area ratio of LIS and LII signals.

LII effective area ratio means the distribution of soot and LIS effective area ratio means the distribution of droplet. High effective area ratio also indicates that the distribution of LIS and LII signals are widely distributed. From this figure, lots of soot is existed in the cylinder immediately after the fuel injected because the mixture formation of this period is not enough to mix air with fuel. And then, the effective area ratios of two injection timings (12° BTDC, 8° BTDC) are gradually decreased with crank angle. However, in case of TDC injection, the trend of effective area ratio is similar as the heat release rate. The maximum value of effective area ratio occurred at the crank angle, which shows the maximum heat release rate. On the other hand, the effective area ratio of this injection timing is higher than other conditions because the injected spray is easy to impact on the piston head, and it results in incomplete combustion.

From these results, 8° BTDC injection was found as most effective injection time to reduce soot formation.

4.3 Effect of swirl on soot distribution

In this study, the effects of swirl on soot distribution were investigated by using LIS and LII signal. (Mitsuru et al., 1992) As shown in this figure, the effective area ratio is remarkably influenced by swirl in all conditions. From the results, it is found that the effective area ratio is

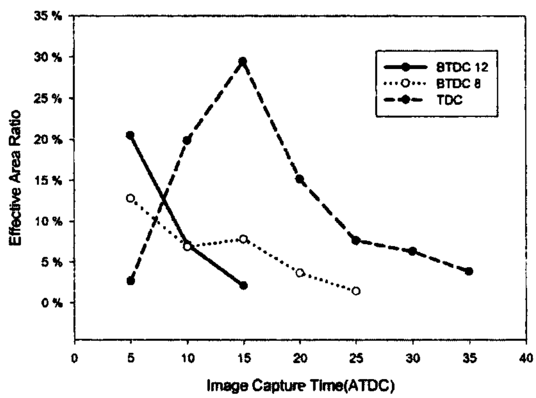


Fig. 10 Comparison of effective area ratio (LII)

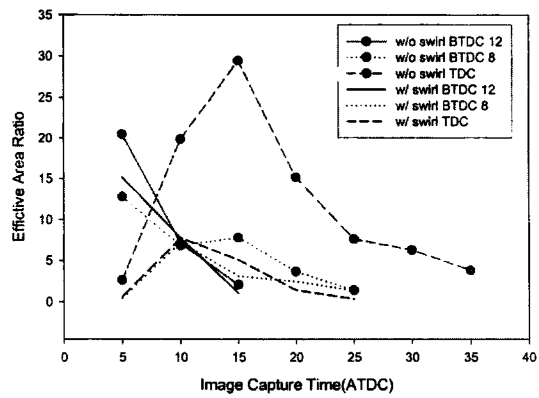


Fig. 12 Comparison of effective area ratio (LII)

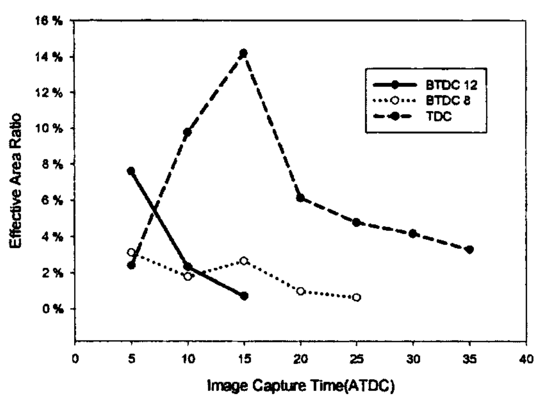


Fig. 11 Comparison of effective area ratio (LIS)

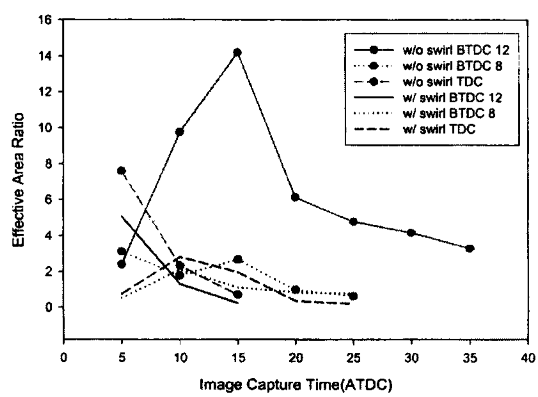


Fig. 13 Comparison of effective area ratio (LIS)

decreased by swirl flow in all conditions. Especially, the effective area ratio in TDC injection case showed a 50% reduction effect. This means that the effect of swirl on soot reduction in TDC injection case is biggest than any other injection timings.

From these results, it is found that swirl is very effective to reduce soot formation because the swirl helps to improve the fuel atomization and enhance the air-fuel mixing.

4.4 Effect of injection timing and swirl on soot formation

To find the optimal combustion condition, the maximum value of effective area ratio on each condition was compared. Figures 14 and 15 show

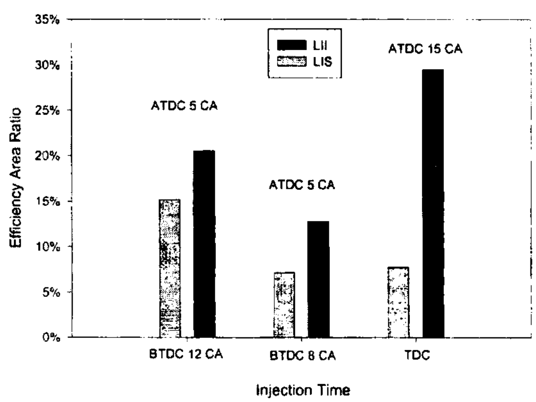


Fig. 14 Comparison of LIS and LII signal (without swirl)

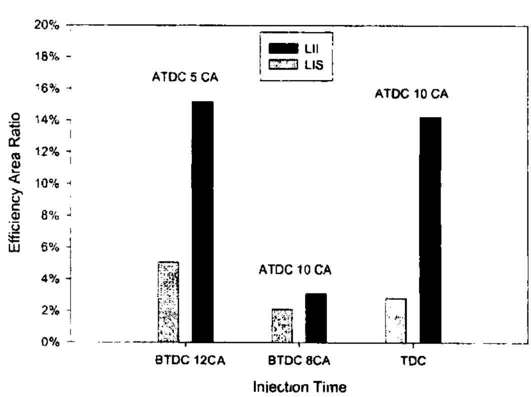


Fig. 15 Comparison of LIS and LII signal (with swirl)

the comparison of the maximum values of effective area ratio between various injection timings.

Comparing two figures, it can be observed that the maximum value of effective area ratio reduced by swirl. This reduction is largest in TDC injection condition. In addition, it can be found that the crank angle, which shows the maximum value in 8° BTDC and TDC injection condition, is changed by swirl. This means that the swirl is more effective in case of the TDC injection. As shown in this figure, the relative minimum value of effective area ratio is appeared in 8° BTDC injection condition. Considering the heat release rate diagram, it was found that the 8° BTDC injection timing is most optimal injection time. From these results, it can be conclude that the 8° BTDC injection timing with swirl is the best condition to improve combustion and to reduce soot formation.

5. Conclusions

In this study, simultaneous LIS and LII experiment system to investigate the distribution of droplet and soot was developed and applied to the diffusion flame in D.I. diesel engine cylinder. From the experiment, it can be concluded that.

(1) The relative number density and diameter of soot were calculated by simultaneous detection of 2-D LIS and LII signals. The distribution of soot was investigated by the developed visualization engine and LII technique.

(2) From the LIS and LII experiments, it was found that the number density of spray inside showed higher value and the larger relative diameter was produced by the fact that the air-fuel mixing in outside region was promoted faster than that of inside region.

(3) The effective area ratio, defined as the ratio of the area contained LIS and LII signals to total horizontal cylinder area, was introduced as a simple indicating factor of soot distribution. From comparing the effective area ratio in various injection timings, 8° BTDC is found to be the best injection timing to improve combustion and reduce soot formation in this operating condition.

(4) The effective area ratio was reduced to 50% level in maximum case under the swirl intensifying condition. Therefore, it was found that the swirl flow was very effective to reduce soot formation and to improve atomization of fuel. Especially, the effect of effective area ratio on the soot formation and fuel atomization was biggest in the TDC injection case.

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