An experimental study on the effect of swirl and injection condition on D.I. diesel combustion using a transparent engine system

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The objective of this work is to investigate the effect of swirl and injection condition on D.I. diesel combustion by using a transparent engine system. The test engine is equipped with common rail injection system to control injection conditions and obtain split injection. In this study, the combustion analysis and steady flow test were conducted to measure the heat release rate from cylinder pressure and the swirl ratio, respectively. In addition, the spray and diffusion flame images were visualized by a high speed camera. The LII&LIS methods were also used to obtain 2-D soot and droplet distribution. As the results, high injection pressure was found to shorten ignition delay as well as enhance peak pressure. The results also revealed that the heat release rate at premixed combustion region was remarkably reduced with a pilot injection, but, the soot distribution and heat release rate at diffusion combustion region were increased. The swirl effect was found to shorten ignition delay at certain injection timing and the swirl generally enhanced heat release rate in all experimental conditions.

1. Introduction

Diesel engines are widely used due to higher thermal efficiency and durability. However, it is well known that the diesel engines emitted excessive nitrogen oxides (NOx) and suspended particulate matter (PM), which has particularly adverse effects on the urban environment. In response to progressively strengthened emission regulations, diesel engines have been developed to reduce these emissions through various means such as the optimization of fuel injection timing and combustion chamber shape and high-pressure fuel injection.

In recent years, high-pressure fuel injection has been considered as a particularly effective method for reducing PM emissions by means of improved atomization and air utilization. Nevertheless, these technologies will not be sufficient to enable diesel engines to meet the stricter emission limits scheduled to be introduced in 2003 and later.

Many researches have been performed to improve exhaust emission. To improve mixing of fuel and air, most common methods are create swirl flow in combustion chamber and high pressure fuel injection using a common rail system.

Swirl flow is known to improve mixing of fuel and air, increasing the ratio of ignitable mixture at the ignition point, and reducing the soot generation[3]. And in case of common rail injection system[4], which is recently attended for its ability of high pressure injection and of control the injection shape and timing, with a high injection pressure, momentum exchange with surrounding air is increased. This is known to have major rule to atomization of fuel and mixing[5].

The objective of this study is to investigate the effect of swirl flow and injection condition on the combustion and soot generation of D.I. diesel engine by means of visualization of spray and diffusion flame in combustion chamber and analyze the characteristic of heat release rate by comparing the LII and LIS images.

2. Experimental apparatus and procedure

2.1. Fuel injection system

Fuel injection system used in this experiment consists of air driven high pressure pumps, a common rail equipped with pressure regulator and electronic-controlled injector. The fuel is pressurized with air driven high-pressure pump and it is supplied to a common rail (accumulator), and then injected into the combustion chamber by a common rail type high pressure diesel injector. The pressure regulator maintains the pressure of the accumulator at a setting point that can be in the range of 500 to 1000bar. The fuel injection nozzle consists of five injection holes. With this system, it is possible to independently control the fuel injection timing and quantity.

2.2. Transparent engine

Engines with optical access to the combustion chamber are often used for the development and optimization of combustion processes, because they allow a direct view into the cylinder. Together with engine testing, a transparent engine was used to find the influence of various engines operating condition. This engine provides optical access to the combustion chamber through a transparent piston. The piston crown is built as a simple bowl with a flat quartz window and the upper piston rings run without lubrication to eliminate fouling of windows caused by lubricant. Rings used in this transparent engine serve as sealing rings allowing extended measurements without obscuring layers on the optical components.

The cylinder head used here is a single cylinder with two valves and designed for direct injection operation within a combustion chamber. In order to investigate the influence of the swirl flow in the cylinder, two types of cylinder heads with different shapes of intake ports have been examined. One is a straight port directing towards the center of the valve. The other is a steep ramp helical port. As steady state analysis, the swirl ratio of the helical port is 2.1 and swirl ratio of the straight port is 0.1.

Table 1 shows the specifications of the transparent engine.

Table 1 Specifications of the transparent engine

Bore×stroke	95mm×95mm	Swirl ratio	0, 2.1
Displacement volume	675cc	Compression ratio	19

2.3. Experimental methods

Regardless of injection pressure and swirl strength, the injection duration is properly adjusted to keep the same air fuel ratio to be 44. The engine is coupled to a DC motor with a speed controller that maintains a speed of 400rpm. The cylinder temperature is fixed at 80˚C. The cylinder pressure was recorded for 40 cycles using the piezoelectric pressure transducer mounted in the cylinder head,.

Instantaneous images of the fuel spray are illuminated using Xenon light passed through the fuel spray. A high speed video camera was used to take the full spectra flame images at 2000fps.

Figure 1 shows the optical system for simultaneous detection of laser-induced incandescence (LII) and laser-induced scattering (LIS). The LII method has emerged as a promising technique for measuring spatially and temporally resolved particulate volume

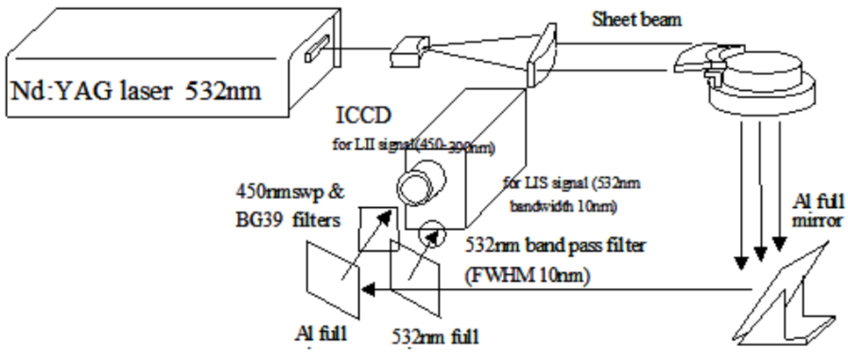


Fig. 1 Schematic diagram of LIS and LII system

fraction and size. In the LII technique, the particulates are heated by a short duration laser pulse. It is well known from numerical models of the heat and mass transfer that the particulate reached peak temperatures of 4000-4500 K if it is stimulated by sufficiently high laser energies. The resultant incandescence, while of short duration, can be readily detected and processed to yield concentration and size information. In general, LII has a temporal resolution of 10ns and can be used to perform both quantitative point measurements and 2-D planar visualization.

A frequency-doubled Nd:YAG laser with a wavelength of 532nm is used in this study. The research single cylinder engine is placed on an optical path along with the Nd:YAG laser head and optics. The incident laser sheet is directed into the combustion chamber.

Both LII and LIS images were taken by a CCD Camera with an image intensifier. A 532nm band pass filter was set in front of ICCD to take LIS image, and a 450nm band pass filter was set to take LII image. Both LII and LIS images were taken by an ICCD camera simultaneously. The experimental conditions listed in Table 2.

Table 2 Experimental conditions

Rail pressure	500,700,1000bar	Injection timing	TDC, BTDC 6°, BTDC10°
Fuel quantity	14.5 mg (w/o swirl), 13.4 mg (w/ swirl)	Air fuel ratio	44
Injection timing	BTDC14°(first injection) TDC (second injection)	Fuel quantity ratio (Q_{first}/Q_{second})	0.3, 0.5

3. Results and discussion

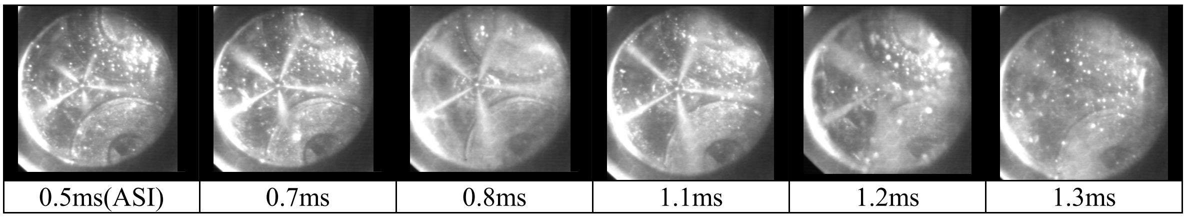
3.1 Spray images of test injector with injection pressure and swirl

Figure 2 shows spray images which are compared with injection pressure and swirl. As injection pressure increases, spray tip penetration becomes large, and fuel sprays impinged upon the cylinder liner and rebounded, which was considered unfavorable.

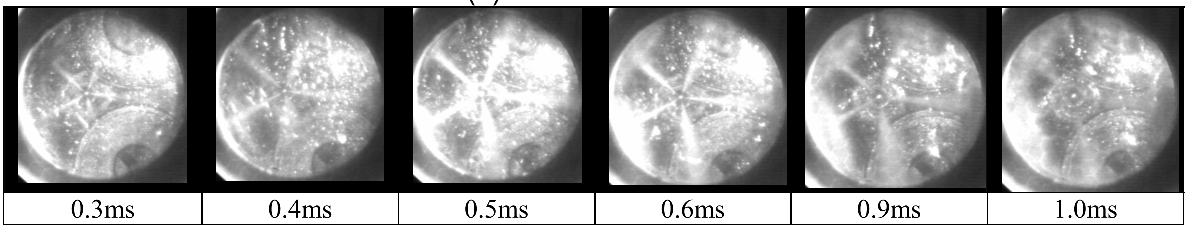
Spray patterns at early stage shows very small differences according to the swirl strength. It is thought that the momentum of the high pressure fuel sprays is much larger than swirl flow.

From observation of spray image, it cab be seen that high injection pressure enhanced atomization of fuel and mixing of air and fuel because it generates the turbulence and incensement of entering air as well as the collision with wall[6)].

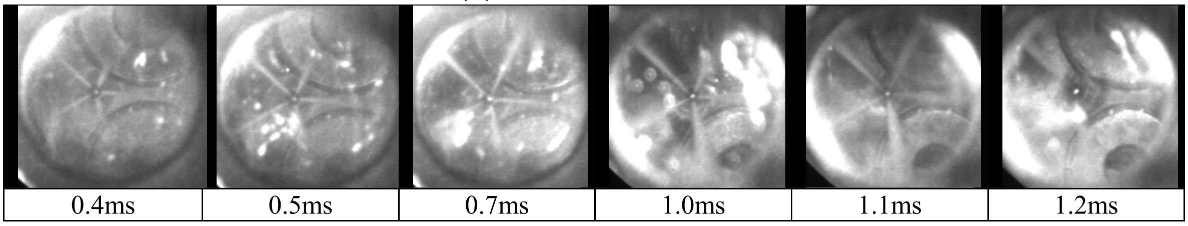
Therefore, it is expected that effect of swirl on spray is much significant at late stage of injection when momentum of injection is reduced and swirl flow influence fuel mixture distribution after the collisions with combustion chamber wall[7)].



(a) 500bar w/o swirl



(b) 1000bar w/o swirl



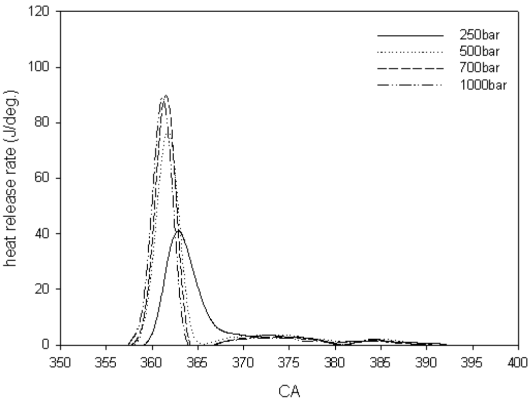
(c) 500bar w/ swirl

Fig. 2 Comparison of spray image with injection pressure and swirl flow

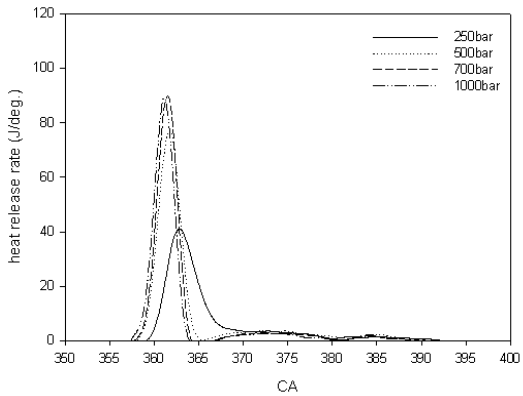
3.2 Combustion characteristics with injection pressure

Figure 3 indicates heat release rate for various fuel injection pressures. In the case of higher injection pressure (above 500bar), heat is released more quickly during a premixed combustion stage. An increment of the injection pressure determines a slight reduction of the ignition delay because of a better spray atomization, a more intense premixed combustion phase with rapid increment of the in-cylinder pressure, and an improvement of the combustion velocity during the mixing-controlled combustion phase due to the better atomization. These trends are similar between two different injection pressures.

Figure 4 shows the combustion process which was observed by a high speed video camera. As can be seen in Fig. 4(b), a bright luminous flame spread quickly over whole combustion chamber area. On the other hand, Fig. 4(a) shows stagnant flames were distributed around wall. From these results, we can find that a more homogeneous mixture can be formed in high injection pressure due to atomization effect, which improve premixing of fuel and air, but air fuel mixture was stagnant around wall and air utilization of center of chamber was relatively low in low injection pressure.



(a) I.T.=BTDC6˚, w/o swirl, A/F=44



(b) I.T.=BTDC10˚, w/o swirl, A/F=44

Fig. 3 comparasion of heat release rate

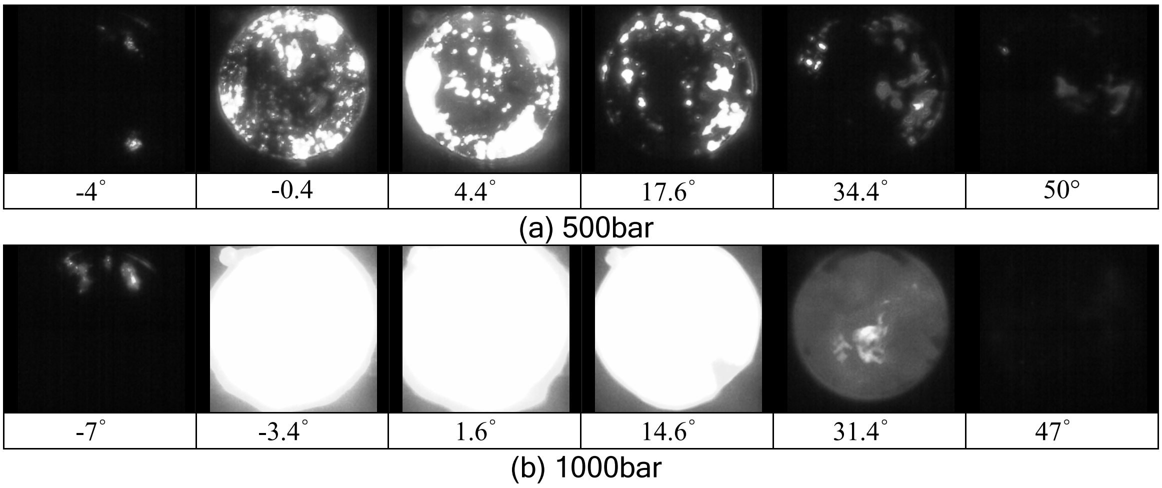


Fig. 4 Comparison of combustion images with injection pressures (I.T.= BTDC 10°)

3.4 Combustion characteristics with swirl flow

Combustion images under various operating conditions are shown in Fig. 5. The combustion image was viewed from the bottom of the cylinder. In case of Fig. 5(a), flame tended to stagnate to combustion chamber wall and around the injector tip, but under swirl condition, mass of bright flame appeared through the whole area, which means that more effective combustion was formed. When injection pressure increased to 1000bar, the luminance of flame in case of swirl flow was a little higher than no swirl condition, but, in a macroscopic view, all the results are similar in distribution and brightness of flame.

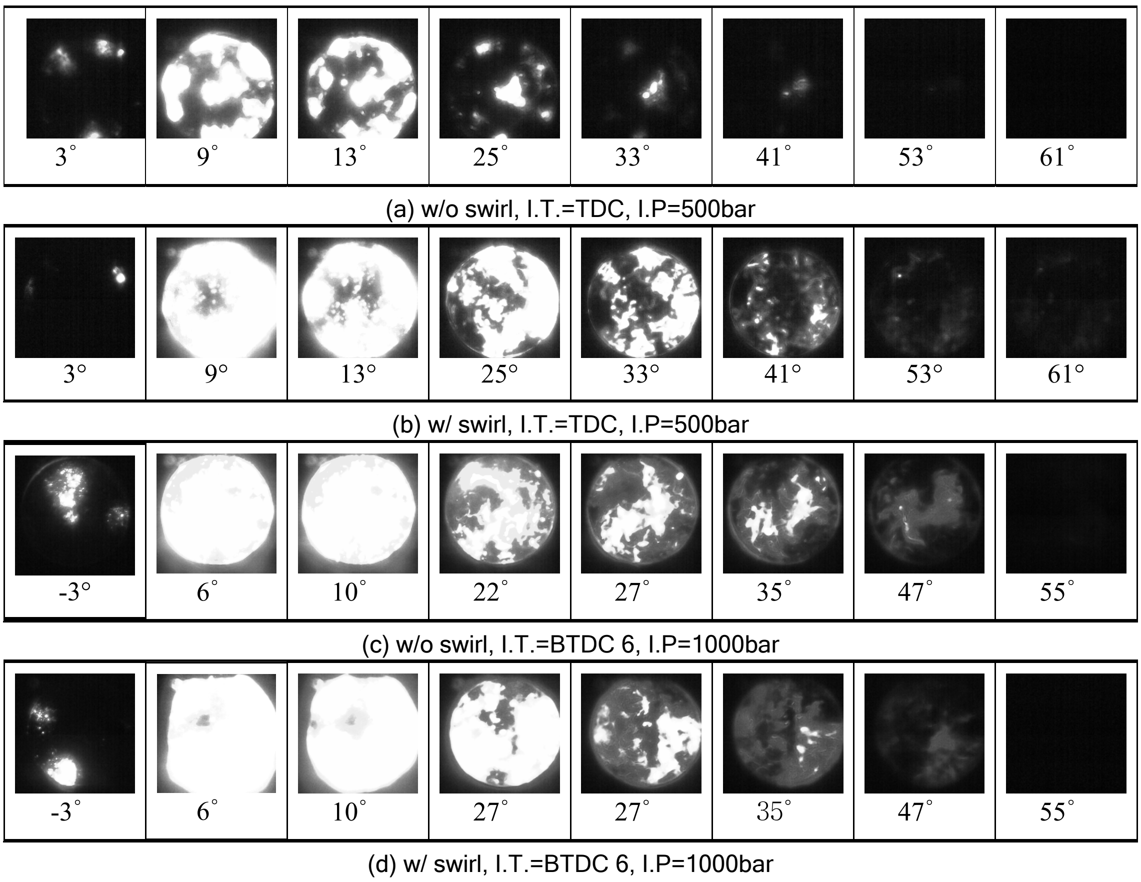
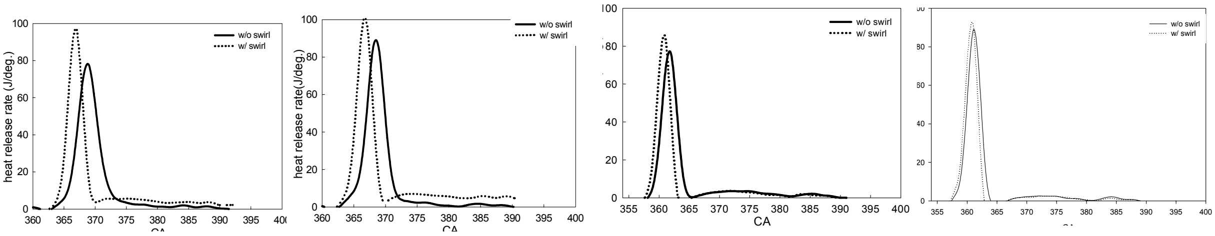
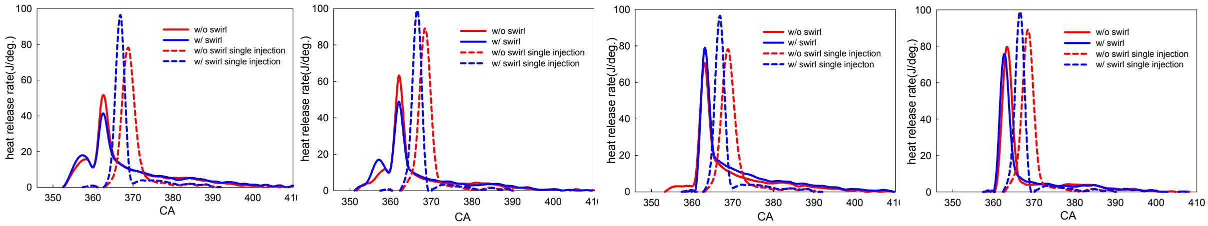


Fig. 5 Comparison of combustion images under various operation conditions



a)I.T.=TDC,I.P.=500bar (b)I.T.=TDC,I.P=1000bar (c) I.T.=BTDC6, I.P.=500bar d)I.T.=BTDC6,I.P.=1000bar

Fig. 6 Comparison of heat release rate



(a)I.P.=500bar,Q_f/Q_s=0.5 (b)I.P.=1000bar,Q_f/Q_s=0.5 (c)I.P.=500bar,Q_f/Q_s=0.3 (d)I.P.=1000bar,Q_f/Q_s=0.3

Fig. 7 Comparison of heat release rate with split injection and swirl flow

A further step was to investigate the effect of the swirl and injection timing on the diesel combustion. The comparison of heat release rate is shown in Fig. 6.

When the injection was started at TDC, ignition delay was almost same period regardless of swirl strength. This trend is same between two injection pressures. On the other hand, the proportion of heat release in premixed combustion region and the peak heat release rate were enhanced by swirl flow in both injection pressures. And in the case of Fig. 6(c), (d), when injection pressure was relatively low at 500bar, ignition delay was shorten and the increasing rate of heat release was enhanced and peak heat release rate were increased, but the swirl flow made little difference in high pressure case. From these results, it is believed that the swirl strength is dominant when mixing time is insufficient. Thus, under the mixing time is sufficient condition, injection pressure is a dominant factor and the effect of swirl flow on the combustion is expected to be low when the injection pressure is relatively high.

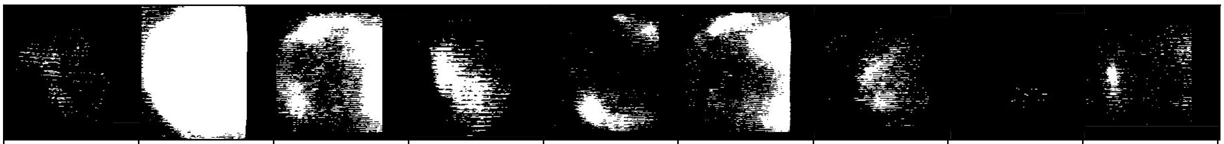
3.5 Effect of spilt injection and swirl flow on combustion

Figure 7 shows the effect of swirl flow and split injection on combustion by comparison of heat release rate.

Pilot injection timing was constantly kept at BTDC 14°, and main injection was TDC. When the ratio of quantity is 50:50(first: second injection), ignition delay was almost same regardless of swirl strength, but it was shorten when injection pressure was 1000bar. The maximum heat release rate was enhanced in first injection region but was decreased during the second injection region. On the contrary, at the ratio 30:70, the maximum heat release rate in first injection region was decreased but it was enhanced during second injection region by swirl flow.

It is believed that injection quantity is relatively large, and swirl strength enhances the mixing of fuel and air because it increases the quantity of ignitable mixture.

From these results, as combustion proceeds during the first injection, ignition delay and mixing time of second injection was shortened, and the first combustion decreases heat release rate in second combustion.



ATDC4	ATDC8	ATDC12	ATDC4	ATDC8	ATDC12	ATDC4	ATDC8	ATDC12

(a)F.I.T.=BTDC10, Q_f/Q_s=10:90 (b)F.I.T.=BTDC10,Q_f/Q_s=30:70 (c)F.I.T.=BTDC6 ,Q_f/Q_s=30:70

Fig. 8 Distribution of soot

3.6 Soot distribution characteristics measured by LII method

Figure 8 shows the temporal sequence of LII images at a given crank angle. Soot distribution within the flame was observed by means of laser induced incandescence (LII). The incandescence of soot particles was achieved by focusing a pulsed UV laser light sheet into the flame. The radiation of the particles heated by this pulse was used to monitor the soot distribution.

As can be seen in Fig. 8, as first injection quantity was increased and the interval between both injections was shortened, the soot generation in flame was reduced.

First stage of soot generation is observed at the center region of combustion chamber and the range is spread out widely. The spread trend of this signal is spatially and temporally similar to that of luminous flame.

During the early stage of diffusion combustion after ATDC 8°, soot distribution region appears along the wall of chamber. At the early stage of combustion, soot particles are generated at this region because there is relatively fuel-rich mixture in chamber center region. However, at the combustion chamber wall region, soot particles are stagnated by quenching effect, which prevents soot burning.

4. Conclusion

In this paper, the effect of various injection condition and swirl flow on combustion was investigated through comparison of heat release rate and LII and LIS images.

From the results, followings were concluded.

(1) High injection pressure tends to shorten ignition delay and enhances peak heat release rate

(2) From the combustion visualization, we found that the intense flame becomes stagnant at combustion wall and the combustion at the chamber center region was incomplete when the injection pressure is relatively low. However at high injection pressure, the flame is observed over all regions

(3) When injection timing is retarded and injection pressure was low, the influence of swirl flow on combustion is relatively significant

(4) When the quantity of first injection is large, swirl flow improves the combustion of first injection and decreases the peak heat release rate of second combustion and vice versa with relatively small quantity of first injection

(5) Soot generation is reduced by increasing quantity of first injection and shortening interval between injections

5. Acknowledgements

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6. Reference

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