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EFFECTS OF A SPLIT INJECTION ON SPRAY CHARACTERISTICS FOR A COMMON-RAIL TYPE DIESEL INJECTION SYSTEM

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ABSTRACT−This work was performed to investigate the effect of a split injection on spray characteristics of fuel sprays injected from a common rail system. In order to analyze the spray behavior and atomization characteristics at various rates of split injections, the injection durations of pilot and main injections were varied in experiments. The injection rate of split injection was measured to study the effect of the pilot injection on the main injection. By using a Nd:YAG laser and an ICCD camera, the development of the injected spray was visualized at various elapsed time from the start of injection. The microscopic characteristics such as SMD and axial velocity were analyzed by using a phase Doppler particle analyzer system. The results indicate that the ambient gas flow generated by the pilot injection affects the behavior of main spray, whereas the effect of pressure variation on the main spray is little. The spray tip penetration of a main spray with pilot injection is longer than that of the single injection by the effect of ambient gas flow. Also the main spray produces larger droplets than the pilot spray due to a small relative velocity between the droplets and ambient gas.

KEY WORDS : Split injection, Spray characteristics, SMD, Common-rail injection system

NOMENCLATURE

SOI : start of injection
D : diameter of droplet
R : radial distance from axis of injector
T_{SOI} : time after start of injection
T_M : duration of main injection
T_P : duration of pilot injection
U : axial velocity of droplet
We : Weber number ($= \rho U^2 D/\sigma$)
Z : axial distance from injector tip
μ : viscosity
ρ : density
σ : surface tension

1. INTRODUCTION

The common rail injection system is able to adjust the injected fuel quantity and injection timing freely in a diesel engine. This electronically controlled injection system also allows the split injection that can reduce the emission of NO_x and a combustion noise in a diesel engine. In order to reveal the combustion mechanism of the pilot injected spray, various researches on the effect of pilot injection on the combustion were performed. Zhang (1999) analyzed the effect of pilot injection on a combustion noise and emission characteristics of a DI diesel engine. He reported that the combustion noise was decreased by the pilot injection, although the smoke has strong trade-off with the combustion noise. Nehmer and Reitz (1994) investigated the effect of split injections on soot and NO_x emissions in a diesel engine experimentally, and revealed out that NO_x emissions were reduced without increase in soot by using 25% or 50% of pilot injection. The combustion mechanism and effect of pilot injection parameters on the engine performance have been widely investigated (Minami *et al.*, 1995; Carlucci *et al.*, 2003).

In an internal combustion engine with an injection system, the spray and combustion characteristics are important parameters for the reduction of HC and NO_x emissions. The spray behavior and atomization performance of split injection seem to be different from those of a single injection because the pilot injection can affect main injection and the combustion characteristics. In order to study the injection characteristics of pilot injection, Henein *et al.* (2002) analyzed the needle lift of an injector, the fuel pressure of a common rail, and the injection rate of a common rail injection system by using a flow rate test rig and a single cylinder research diesel engine. Bianch *et al.* (2002) suggested a numerical analysis of injection profile model of a high-pressure

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common rail injector.

Many other researchers (Park and Lee, 2003; Demoulin and Borghi, 2002; Lee and Park, 2002; Gao and Schreiber; 2001) have also reported the effect of injection parameters on the combustion, emission, and injection characteristics of a common rail injection system based on the experimental and numerical results. However, the previous researches on the atomization characteristics of the split injection have been mainly focused on the engine performance, combustion and emissions in the engine, and injection characteristics such as flow rate and injection rate. Considering that the atomization characteristics such as mean droplet size and velocity distributions are major factors in engine performance, the experiments on the atomization characteristics are significant for the better understanding on the evaporation and combustion processes.

The aim of this study is to investigate the atomization characteristics of a diesel fuel spray injected from the common rail system with pilot injection by using a phase Doppler particle analyzer system and a spray visualization system at various injection durations of the pilot spray. The macroscopic characteristics were obtained from the spray visualization system. On the other hand, the SMD and velocity distributions of injection spray were analyzed by using the droplet analyzing system.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

Experiments were performed to visualize the process of spray development and to obtain the mean diameter and velocity distributions of pilot and main sprays. The injection rate was also measured to compare the injection profiles of a split injection with a single injection. The time durations of pilot and main sprays were varied for investigating the rate of pilot spray on the atomization performance. The injection pressure was set equal to 60 MPa that is corresponding the injection pressure during partial load conditions in a diesel engine, and the total injection duration was fixed as 1.2ms, whereas the duration of pilot and main injections were varied respectively. The detailed experimental conditions are listed in Table 1.

2.1. Fuel Injection System and Common-rail Injector

In this study, a high-pressure injection system was made for an easier control of injection pressure in comparison to the commercial high-pressure pump for common rail injection system. For the injection of a spray, two high-pressure pumps (Haskel, HSF-300) that are operated by compressed air, generate a high-pressure of fuel and store it in the common-rail. The pressure regulator and the quantity of the inlet air control the pressure of common-rail. The schematic diagram of the fuel injection system is shown in Figure 1.

Table 1. Experimental conditions.

Duration of pilot injection [ms]	0	0.4	0.5	0.6
Duration of main injection [ms]	1.2	0.8	0.7	0.6
Injection pressure [MPa]		60		
Ambient pressure [MPa]		0.1		
Ambient temperature [K]		293		
Nozzle L/D ratio		2.67		

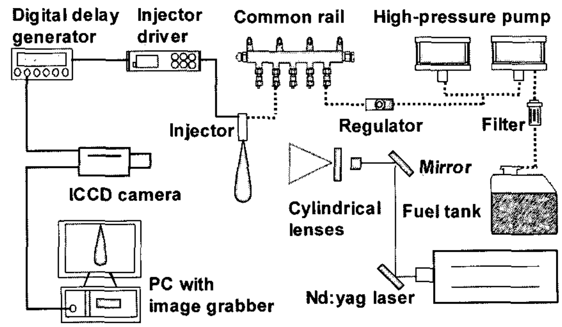


Figure 1. Schematic diagram of spray visualization system with a high-pressure pump.

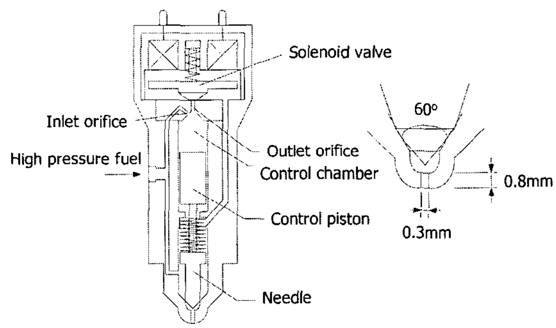


Figure 2. Configuration of a common-rail injector.

The injector that was used in this work is mini-sac type injector designed for common-rail injection system. It has single nozzle with diameter of 0.3 mm and depth of 0.8 mm, and is controlled by the peak current of 16.0A and holding current of 5.0A. The injector driver and a time delay generator controls injection timing and durations of pilot and main sprays. The configuration of the injector and the shape of the hole are illustrated in Figure 2.

2.2. Spray Visualization System and Injection Flow Meter

The macroscopic structure of the spray such as spray tip

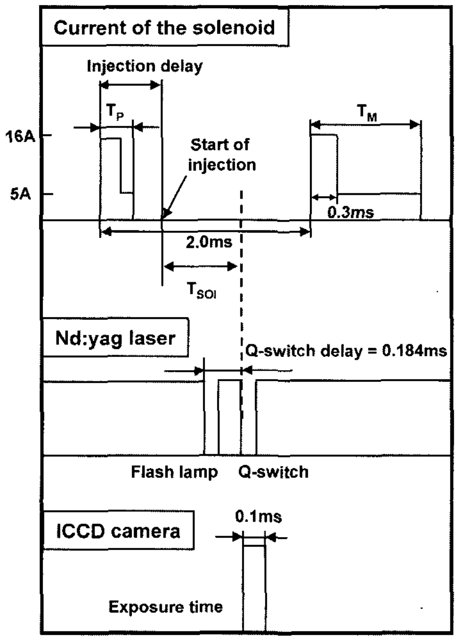


Figure 3. Timing chart of synchronization.

penetration and overall behavior can be obtained directly from the frozen images from the spray visualization system as shown in Figure 1. The visualization system is composed of a Nd:YAG laser (Continuum, SL2-10), cylindrical lenses, a time delay generator, and an ICCD camera (Stanford Computer optics, 4 Quick 05A). Single image was captured from an injection of the spray at a specific time after start of injection. The time delay generator synchronizes the injection signal to the driver, the ICCD camera, and the firing signal of the Nd:YAGlaser.

Figure 3 shows the timing chart of the synchronization. In this experiment, the time after start of injection (T_{ASOI}) is set to zero when the spray tip is visible at the nozzle tip. The images were captured at every 0.2 ms from the start of injection, and spray images were obtained and averaged at the same elapsed time to reduce the experimental error. The flash lamp discharge voltage of the Nd:YAG laser and the (micro channel plate) voltage of the ICCD camera were set to 1.40 kV and 450 V based on the brightness of the image. The laser emits a beam with approximate 10 mm of diameter, 532 nm of frequency, and 5 nsec of pulse duration. The guided beam by the mirrors passes through a cylindrical lens with −10 mm of focal length and expands the beam height vertically. The beam then passes through a positive cylindrical lens with 300 mm focal length to reduce the thickness of the beam horizontally. The line beam generated by two cylindrical lenses has thickness less than 0.5 mm and height of 300 mm at the measuring section.

An injection rate meter (Bosch, 1966) which is simple method and used widely (Ikegami *et al.*, 1997; Assanis *et al.*, 2000) was used to determine the time resolved injection profile. This apparatus is based on the pressure change of a tube filled with fuel when the fuel is injected to the tube. During the experiment, the pressure in the tube was set equal to 4 MPa. A pressure sensor of piezo type was utilized to measure a pressure of the tube, and 300 continuous injections were averaged for a test case.

2.3. Droplet Analyzing System

The mean droplet size distribution was measured by phase Doppler particle analyzer (PDPA) system shown in Figure 4. It consists of a laser light source, optical arrangements, a transmitter, and a data acquisition system. Based on the data rate and the signal intensity of the signal analyzer, the laser output of Ar-ion laser and the PMT voltage were determined to 1.5W and 500V, respectively. The sub-range of the diameter, the effective rage of the PDPA signal analyzer, was from 2 μm to 100 μm. At each measurement point illustrated in Figure 5, approximately 20,000 droplets were captured and averaged.

In order to obtain the time resolved data, the signal

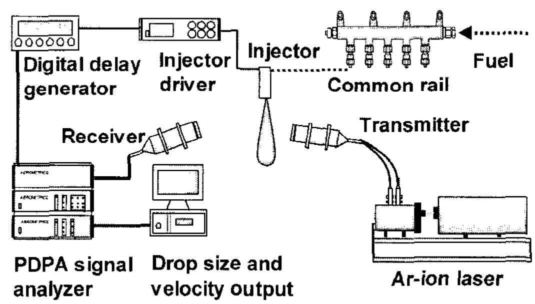


Figure 4. Phase Doppler particle analyzer system.

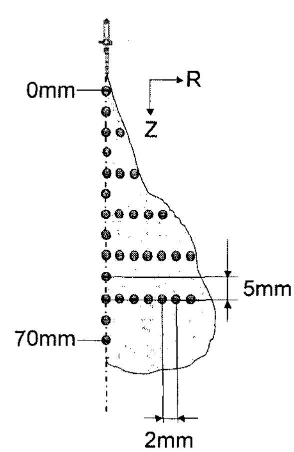


Figure 5. Measurement points of experiment.

Table 2. Specifications of the PDPA system.

Wave length	514.5 nm, 488 nm
Laser beam diameter	1.4 mm
Fringe number	36
Focal length	500 mm for Transmitter
Focal length	500 mm for Receiver
Collection angle	30°
Laser output	Ar-ion, 5 W(max)

Table 3. Effect of injection duration on injected fuel mass.

Injection durations [ms]	Quantity injected [mg/injection]
T_P=0.0, T_M=1.2	15.26
T_P=0.4, T_M=0.8	12.07
T_P=0.5, T_M=0.7	11.10
T_P=0.6, T_M=0.6	9.25

analyzed was synchronized with the injection driver by the delay generator. The representative SMD at a specific time was determined by averaging the captured droplets at all of the measurement points shown in Figure 5. The detailed specifications of PDPA system are listed in Table 2.

3. RESULTS AND DISCUSSION

The spray characteristics of a diesel spray with pilot injection were analyzed in terms of injection rate, spray tip penetration, mean size distribution, and droplet velocity distribution by using the injection rate meter, the spray visualization system, and the phase Doppler particle analyzer system. The duration of pilot injection was varied, whereas the total injection duration was fixed as 1.2 ms.

3.1. Injection Characteristics

The pressure variation in a common rail is postulated from the injection rate quantitatively. Figure 6 shows the injection rate as a function of time after start of energizing at various injection durations. In this figure, the time is set to zero when the solenoid of the injector starts to energize. As illustrated in this figure, the injection delay is about 0.25 ms in all test cases. The flow rate profile of the main injection is similar with that of the pilot injection when both pilot and main injection

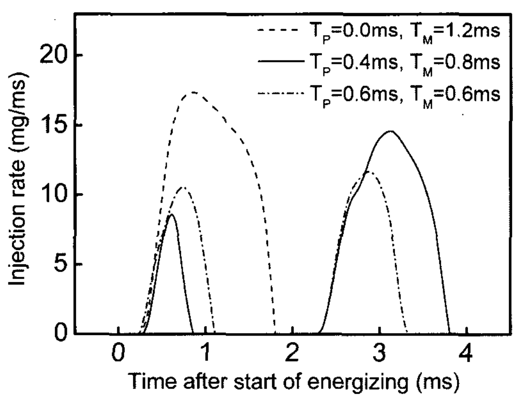


Figure 6. Effect of injection duration on injection profile.

durations are equal to 0.6 ms. This trend indicates that the pressure variation caused by the pilot injection has little effect of the injection on the main spray.

Table 3 lists the fuel mass injected at various duration of pilot injection. The injected fuel quantity per one cycle was obtained by averaging the total mass from 1,000 injections. As can be seen in the table, the single injection has the largest fuel mass injected of all the test cases. In addition quantity of injected fuel becomes smaller for longer duration of pilot injection. This pattern coincides with the results of injection rate and the previous studies (Nehmer and Reitz, 1994; Henein *et al.*, 2002) that indicate the injection rate of pilot injection is smaller than that of main injection, because the injection rate is increasing.

3.2. Macroscopic Behaviors of Spray

The macroscopic behaviors such as the spray images and

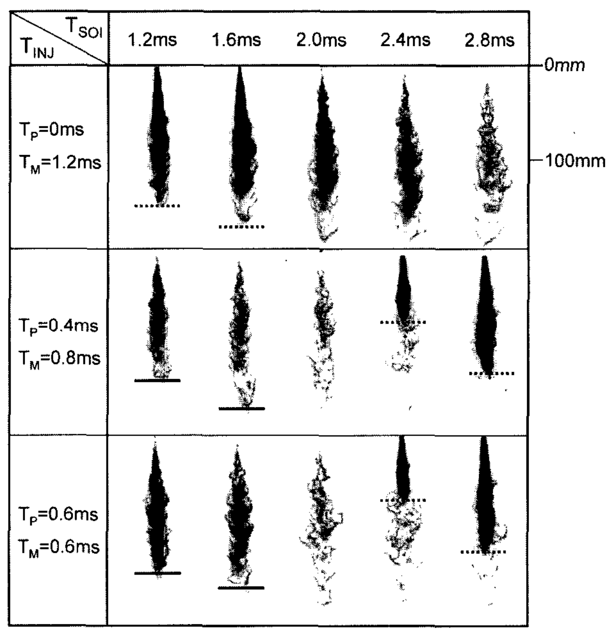


Figure 7. Development of diesel fuel sprays injected at 60 MPa (Solid and dashed lines indicate tip of pilot spray and tip of main spray, respectively.).

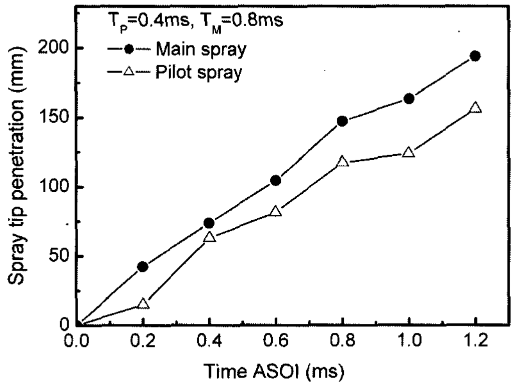
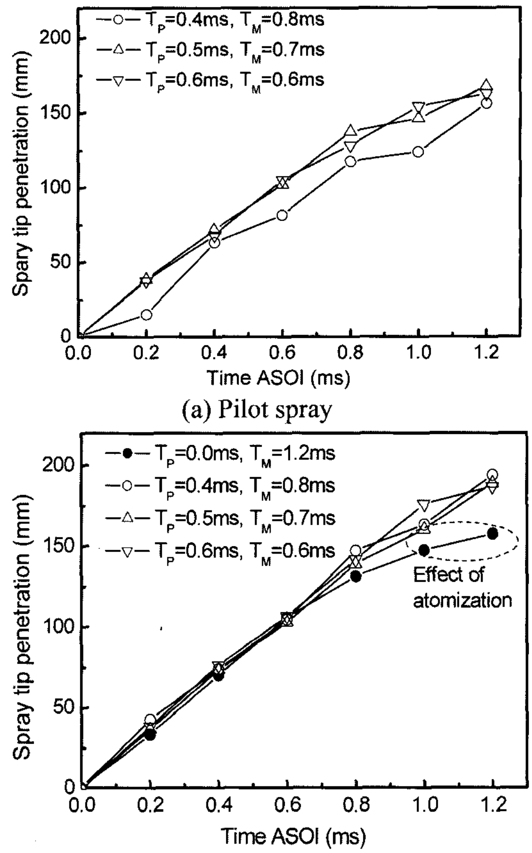


Figure 8. Effect of pilot injection on spray tip penetration.

spray tip penetration were analyzed from the frozen images of various elapsed times after start of injection. Figure 7 illustrates the process of spray development in terms of elapsed time after start of injection. In this image, the bright level of spray was reversed for better expressions of the images pilot injection. In the case of single injection, the spray grows during injection duration and becomes dilute after the end of injection. At the injection timing of main spray, 2.0 ms after start of injection, the diluted distribution of fuel spray that can affect the behavior of main spray is observed. In the cases of the split injections, the main spray is visible in the frozen image at 2.4 ms after start of injection. As shown in the image at 2.4 ms, there may be some effects of pilot spray on the behavior of main spray. As revealed from the results of injection rate, the pressure variation due to the pilot injection is negligible. However the ambient gas flow may affect on the development of the main spray. The relative velocity between the ambient gas and droplets of main spray also can be reduced because the pilot spray goes downstream.

In order to analyze the effect of pilot spray on the behavior of main spray, the comparison of spray tip penetration between the pilot and main sprays is shown in Figure 8. In this figure, the mean velocities of spray tips are 130 m/s for the pilot spray and 162 m/s for the main spray, which indicate the main spray is faster than the pilot spray. Considering the effect of ambient gas flow generated by pilot spray, it can be guessed that the ambient gas flow by high velocity of main spray causes the longer spray tip penetration of main spray than that of pilot spray.

Figure 9 compares the spray tip penetrations of the pilot spray and main spray according to the injection duration. The penetrations of pilot sprays are shown in Figure 9(a). It can be seen that three cases have similar trend in spray tip penetration, whereas the spray tip penetration of T_P=0.4 ms is a little shorter than that of



(a) Pilot spray

(b) Main spray

Figure 9. Spray tip penetrations according to the injection duration.

T_P=0.5 ms or T_P=0.6 ms. As shown in figure, the injection duration, 0.4 ms, may be too shorter to issue stable liquid jet. This postulation can be supported by the injection rate profile of Figure 6 that indicates the fuel mass injected is small at 0.4 ms of pilot injection. In the cases of T_P=0.5 ms and T_P=0.6 ms, the stable liquid jets are injected, therefore, there is little differences between them.

The comparison of main spray tip penetrations is illustrated in Figure 9(b). Before 0.8 ms after start of injection, every main spray grows almost linearly, which can also inform that the pressure variation in the common rail due to pilot injection is not so effective on the injection of main spray. On the other hand, after 0.8 ms after start of injection, there are observed some difference between the sprays with and without pilot injection, as illustrated in this figure. The tip penetrations of main sprays with pilot injection still increase almost linearly, whereas penetration of single injection decreased. In the case of single injection, the relative velocity between the main spray and ambient gas is large because it is injected into stagnant gas. The large relative velocity promotes the

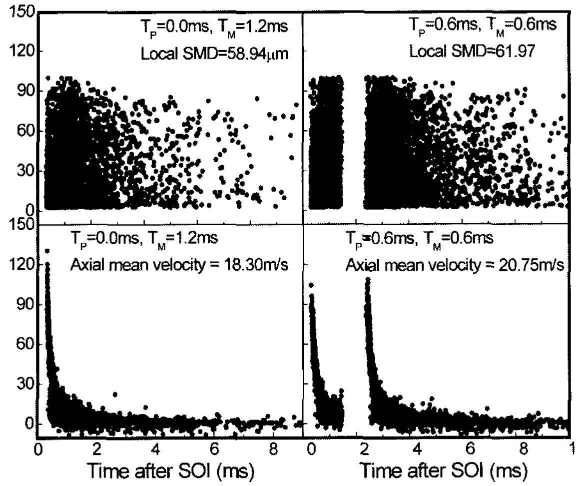


Figure 10. Diameter and axial mean velocity distribution (Z=10 mm, R=0 mm).

atomization of spray, and the enhanced atomization decreases the spray tip penetration.

3.3. Spray Characteristics

The effects of pilot injection on the spray characteristics were analyzed quantitatively in terms of time resolved SMD and axial mean velocity distributions. Figure 10 compares the size and velocity distributions of droplets from single injection (left figure) and split injection (right figure) at 10 mm downstream from the nozzle tip. The split injection shows two separated stages of injection as illustrated in the figure, and has larger SMD and higher velocity than the single injection. The higher velocity indicates that the ambient gas flow downstream reduces a drag on the spray. The larger SMD also can be explained as the smaller relative velocity due to the ambient gas flow generated by the pilot injection.

Figure 11 shows the overall SMD and mean velocity

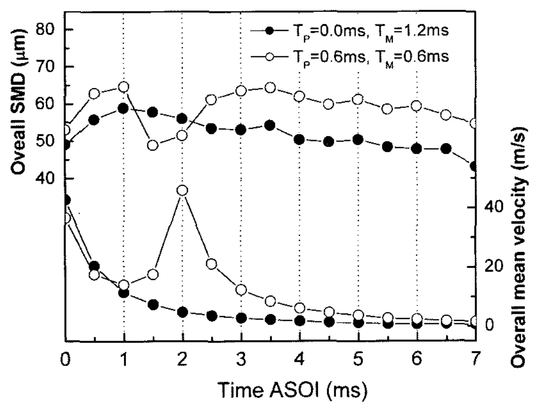


Figure 11. Effect of pilot injection on overall SMD and mean velocity.

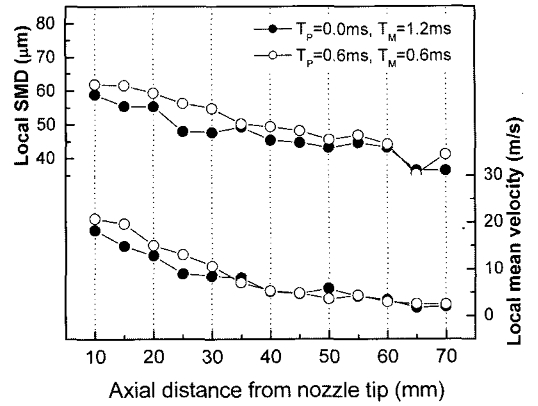


Figure 12. SMD and mean velocity distributions according to axial distance.

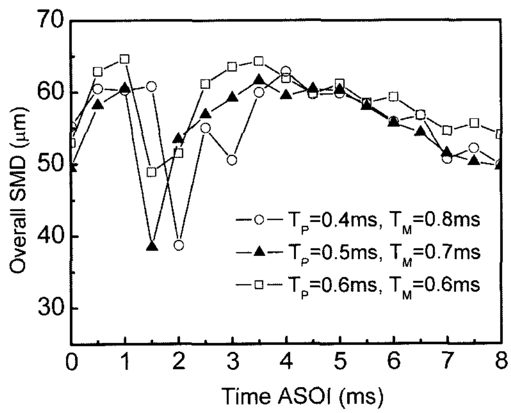


Figure 13. Effect of duration of pilot injection on time resolved overall SMD.

as a function of time after start of injection. In this study, the overall values are obtained by averaging the data of all measurement points illustrated in Figure 5, and a local value indicate the results of a specific measurement point. In the case of fuel spray with pilot injection, sudden increases in SMD and velocity are observed near the start of main injection. It can be seen that the large droplets with high speed injected by main injection cause this trend. After the start of main injection, the SMD of spray with pilot injection is larger than that of the spray with single injection because of the ambient gas flow generated by the pilot injection.

With the time resolved atomization performance, the spatial distributions of SMD and velocity are also important on the atomization characteristics of fuel spray. The spatial characteristics of atomization, local SMD and velocity, are illustrated in Figure 12. This figure indicates that the SMD and axial mean velocity are decreased as the axial distance is increased. As can be seen in this figure, the SMD and axial mean velocity of the spray

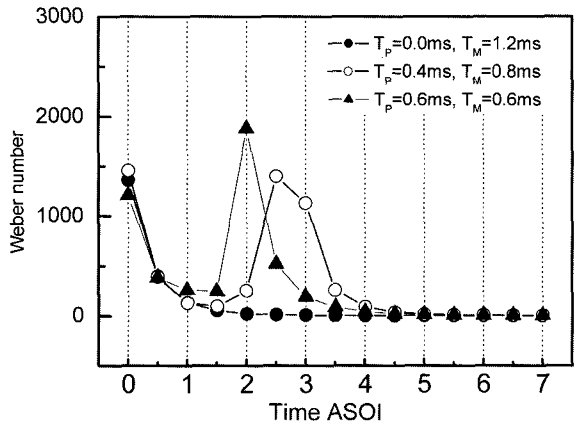


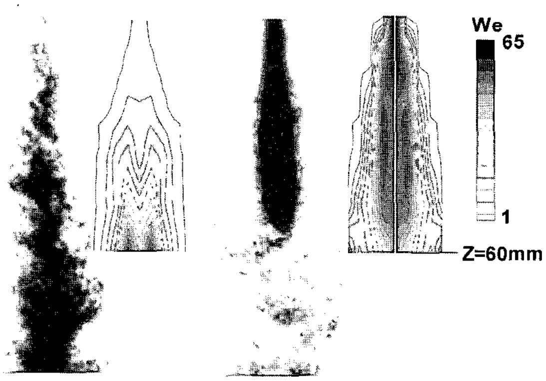
Figure 14. Weber number as a function of time after start of injection.

with pilot injection are larger than those of the spray with single injection above 30 mm, whereas the difference is decreased beyond 30 mm. Considering the difference is reasoned from the effect of ambient gas flow, it can be postulated that the effect of ambient gas flow is reduced beyond 30 mm.

Figure 13 shows the effect of pilot injection duration on the overall SMD of the spray. As shown in the figure, the effect of injection duration of pilot spray on the time resolved overall SMD is negligible. From the results of SMD distribution, it can be said that pilot spray affects on the main spray, whereas injection duration of pilot spray is not so effective.

The breakup of droplet is related closely with the Weber number. By analyzing the correlations of Weber number and the atomization characteristics, time resolved Weber number is shown in Figure 14. In this figure, the distribution of Weber number is similar with the mean droplet size and axial mean velocity shown in Figure 11.

The Weber number can be regarded as an index of



(a) T_P=0ms, T_M=1.2ms (b) T_P=0.6ms, T_M=0.6ms

Figure 15. Spatial distribution of Weber number.

possibility of droplet breakup. If the Weber number is high, it can be said that the possibility of breakup is high. Therefore the Weber number is important on understanding the atomization characteristics.

Figure 15 shows the spatial distribution of the Weber number with the visualized image of the spray at 2.4 ms after start of injection. In the case of single injection, the Weber number is very low in comparison to the single injection. This may indicates that the atomization process has almost finished at 2.4 ms after start of injection. On the other hand, the Weber number distribution of split injection shows that the breakup may occur actively at the illustrated time.

4. CONCLUSIONS

In this study, the effects of pilot injection on the spray characteristics were studied by analyzing the profile of injection rate, process of spray development, SMD, and axial mean velocity. To obtain the images of spray, mean droplet size, and velocity, the visualization system and phase Dappler particle analyzing system were utilized. The effects of the variation in the injection pressure and the ambient gas flow on the spray characteristics were investigated. The conclusions of this study can be summarized as follows:

(1) The results of injection profile, spray tip penetration, and SMD distribution indicate that the effect of ambient gas flow is more dominant in the spray characteristics in comparison with the effect of pressure variation.
(2) The spray tip penetration of main spray with pilot injection is longer than that of single injection. The reduced drag due to the ambient gas flow generated by the pilot injection may cause this trend.
(3) The pilot injection has some negative effects on the atomization of the main spray because the ambient gas flow created by the pilot injection decreases the relative velocity between the droplet and ambient gas. The larger time resolved SMD is measured in the case of split injection. However the difference of SMD between single and split injections is decreased as the spray flow downstream.
(4) The injection duration effect of pilot spray on the atomization performance is little in comparison with the difference between single and pilot injections. The Weber number shows similar trend with the SMD or axial mean velocity.

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REFERENCES

Assanis, D. N., Filipe, Z. S., Fiveland, S. B. and Syrimis,

M. (2000). A methodology for cycle-by-cycle transient heat release analysis in a turbocharged direct-injection diesel engine. *SAE Paper No.* 2000-01-1185.

Bianchi, G. M., Falfari, S., Pelloni, P., Kong S. C. and Reitz, R. D. (2002). Numerical analysis of high-pressure fast-response common rail injector dynamics. *SAE Paper No.* 2002-01-0213.

Bosch, W. (1996). The fuel rate indicator: A new measuring instrument for display of the characteristics of individual indicator. *SAE Paper No.* 660749.

Carlucci, P., Ficaralla, A. and Laforgia, D. (2003). Effect of pilot injection parameters on combustion for common rail diesel engines. *SAE Paper No.* 2003-01-0700.

Demoulin, F. X. and Borghi, R. (2002). Modeling of turbulent spray combustion with application to diesel like experiment. *Combustion and Flame,* **129**, 281–293.

Gao, Z. and Schreiber, W. (2001). The effects of EGR and split fuel injection on diesel engine emission. *Int. J. Automotive Technology* **2**, **4**, 123–133.

Henein, N. A., Lai, M. C., Singh, I. P., Zhong, L. and Han, J. (2002). Characteristics of a common rail diesel injection system under pilot and post injection modes. *SAE Paper No.* 2002-01-0218.

Ikegami, M., Nakatani, K., Tanaka, S. and Yamane, K. (1997). Fuel injection rate shaping and its effect on exhaust emissions in a direct-injection diesel engine using a spool acceleration type injection system. *SAE Paper No.* 970347.

Lee, C. S. and Park, S. W. (2002). An experimental and numerical study on fuel atomization characteristics of high-pressure diesel injection sprays. *Fuel* **81**, **18**, 2417–2423.

Minami, T., Takeuchi, K. and Shimazaki, N. (1995). Reduction of diesel engine NOx using pilot injection. *SAE Paper No.* 950611.

Nehmer, D. A. and Reitz, R. D. (1994). A study of pilot injection in a DI diesel engine. *SAE Paper No.* 940668.

Park, S. W. and Lee, C. S. (2003). Macroscopic structure and atomization characteristics of high-speed diesel spray. *Int. J. Automotive Technology* **4**, **4**, 157–164.

Zhang, L. (1999). A study of pilot injection in a DI diesel engine. *SAE Paper No.* 1999-01-3493.