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A Study on the In-cylinder Flow Characteristics of GDI High-pressure Fuel Injector Using a Transparent Engine System

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The direct-injection spark ignition engine is one of the promising gasoline engine designs for achieving higher engine performance and lower fuel consumption while maintaining the excellent driving performance and low emissions. Thus an in-cylinder spray flow motion plays an important role in the adjustment of mixture preparation with a fundamental spray characteristics and in-cylinder flow field as well. In this study, the fundamental spray characteristics such as drop size, velocity distribution, spray angle, in-cylinder spray flow motion in order to optimize intake port, piston top land and combustion chamber shapes in the development stage of mass-produced GDI engine. For this purpose, the PDPA measurements and Mie scattering technique were used for detailed spray characteristics. In-cylinder spray motions were captured by ICCD camera through the single-cylinder optical engine. From the experimental results, the test injector shows a good low-end linearity between the dynamic flow and fuel injection pulse width and the fuel spray of 20μm or less in SMD with good spray symmetry. In addition, the in-cylinder tumble flow has more effect on the homogeneous mixture formation than that of in-cylinder swirl flow at early injection mode and the in-cylinder swirl flow plays a better role of stratified mixture preparation than tumble flow at late injection mode.

Keywords: direct-injection gasoline engine, in-cylinder spray flow motion, single-cylinder optical engine

INTRODUCTION

The exhaust emissions from automotive engine such as unburned hydrocarbon, carbon monoxide and nitrogen oxides have impact on the air pollution and environment contamination. And the carbon dioxide from automotive emissions has also had a tremendous effect on the global warmth. Thus, the restrictions on these exhaust emissions are becoming more stringent.

The direct-injection spark ignition engine is one of the promising gasoline engine designs for achieving higher engine performance and lower fuel consumption while maintaining the excellent driving performance and low emissions. The injection of gasoline directly into the cylinder of a spark ignition engine is a concept that offers numerous potential advantages over the current port-injection systems that inject fuel into the engine intake port. The major advantage of direct-injection gasoline engine compared to the port-injection engine is that it doesn't have additional mixture preparation stage which causes liquid fuel film on the intake port. In this point of view, it is becoming more important to analyze the fundamental spray characteristics such as SMD (Sauter mean diameter) level, drop size distribution, droplet velocity, spray angle, and in-cylinder spray flow motion. In general, high-pressure swirl-type injectors are well used to minimize mean drop size and to adjust air-fuel mixture preparation in direct-injection gasoline engines.

Zhao et al.(1)*, Fraidl et al.(2), Ando(3) and other researchers have described reviews of liquid atomization mechanism and spray characteristics for direct-injection gasoline engine applications. The detailed spray structure of high-pressure swirl-type injector, which is installed to direct-injection gasoline engine, was investigated experimentally by use of phase Doppler method and Mie scattering technique (4, 5, 6). However, the most of previous studies on the spray characteristics focus on the spray visualization and the quantitative analysis of atomization characteristics, which indicate that there exists a limit to application of mass production GDI engine design.

In this study, the fundamental spray characteristics of the high-pressure swirl-type gasoline injector and in-cylinder spray flow motion under motoring condition were investigated in order to optimize mixture formation process in the development stage of mass production GDI engine. For this purpose, the authors applied phase Doppler particle analyzer (PDPA) system and Mie scattering technique to the high-pressure gasoline injector. The test injector was then installed to the single cylinder optical engine, which was designed for gasoline direct injection engine application and to give a good optical access while retaining most of the features of a typical production engine. By use these optical engine and camera imaging system, the authors could obtain the in-cylinder spray flow motion successfully under engine operating condition.

EXPERIMENTAL APPARATUS AND PROCEDURES

ENGINE DESIGN

Single-cylinder optical engine used here was designed for GDI engine application and to give a good optical access while retaining most of the features of a typical production engine. The engine has a 4-valve pent-roof type cylinder

* Numbers in parentheses designate references at the end of paper

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head with high-swirl and non-swirl intake port as shown in Figure 1. The swirl control valve (SCV), which was installed at high-swirl intake port (referred to as primary intake port) generates the high in-cylinder swirl flow required for stable lean burn operation at part load and low engine speed. The non-swirl intake port (referred to as secondary intake port) generates the in-cylinder tumble flow which is transformed into turbulence near TDC by tumble deformation so as to enhance air-fuel mixing and increase flame propagation rate for power operation mode at full load and high engine speed. The intake port angle is 39 degrees, which is allowable space to install high-pressure gasoline injector at the bellow of the intake port. Figure 2 shows the fuel injector and SCV location. The fuel injector is mounted at the bore edge between the intake valves and the injector inclination angle is 30 degrees.

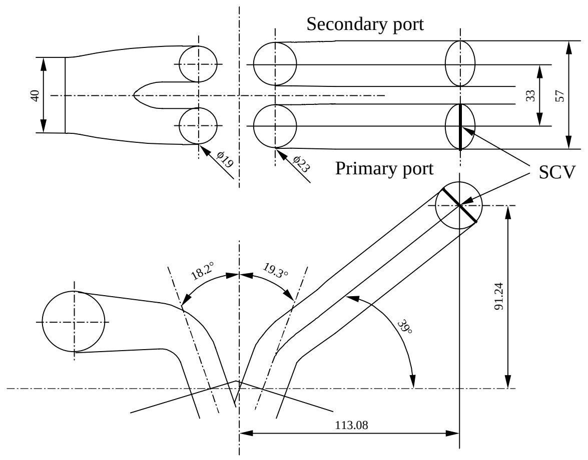


Figure 1. Intake port geometry of GDI engine

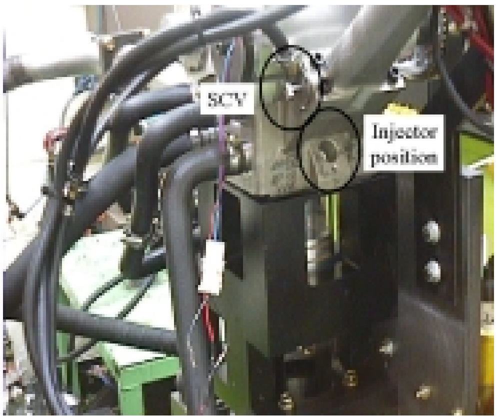
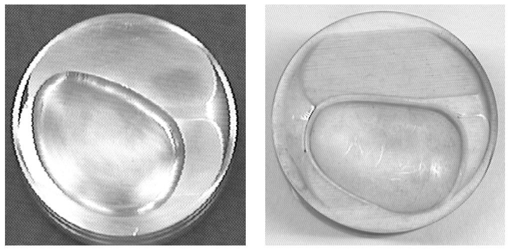


Figure 2. Photography of SCV and Injector position

Two types of piston head were designed as a concept of an off-axis piston bowl, fuel injection onto the bowl wall, and a central spark plug configuration shown in Figure 3. These systems use an in-cylinder swirling flow to stabilize the mixture stratification. The Bowl volumes are 14.8cc and 7cc of piston type A and B respectively. The bottom curvature of the bowls and the height of top face are 4mm and 6.7mm for piston type A, and 25mm and 5.8mm for piston type B respectively. The bottom curvature of the bowl is a important design factor to the HC emission formation in the bowl while the height of top face of piston has a influence on the in-cylinder tumble flow. Table 1 shows the general specifications of the test engine.



(a) Piston type A (b) Piston type B

Figure 3. Photography of piston head shape

EXPERIMENTAL SETUP

A schematic outline of the experimental setup is shown in Figure 4. In-cylinder spray motion was visualized by using a intensified charge coupled device (ICCD) camera and halogen lamp of 1kW maximum power. The ICCD camera (4Quick05A, Stanford Computer Optics), which has 768(H)×480(V) pixels of spatial resolution, was aligned at off-axis to visualize spray flow motion in combustion chamber through the quartz cylinder liner. The camera was synchronized with a timing controller to capture at a pre-decided crank angle position. The crank angle position was detected by using a rotary encoder (3600ppr, AVL) installed at a DC dynamometer (50kW, Hydra, Richardo).

Table 1 – Specifications of test engine

Engine type	4 stroke,1 cylinder 4 valve, DOHC	
Bore × Stroke	79.0mm × 81.5mm	
Displacement	374.6cc	
Compression ratio	11.2	
Combustion chamber	Pentroof type	
Valve timing	IVO	13° BTDC
	IVC	41° ABDC
	EVO	43° BBDC
	EVC	11° ATDC

Pre-experiments were conducted to investigate the fundamental spray characteristics of the high-pressure gasoline injector. Mie scattering technique was used here to obtain the spray developments and overall structure at the vertical and horizontal section of the fuel injection. For the analysis of detailed spray structure, droplet size and velocity distributions were measured by use of PDPA system. The PDPA system consists of Ar-ion laser (Coherent, Innova 70C), fiber drive, beam separation prism, beam transmitter, receiver, signal processor (Aerometrics, RSA1000), and traverse system. The general specifications of PDPA are listed in Table 2.

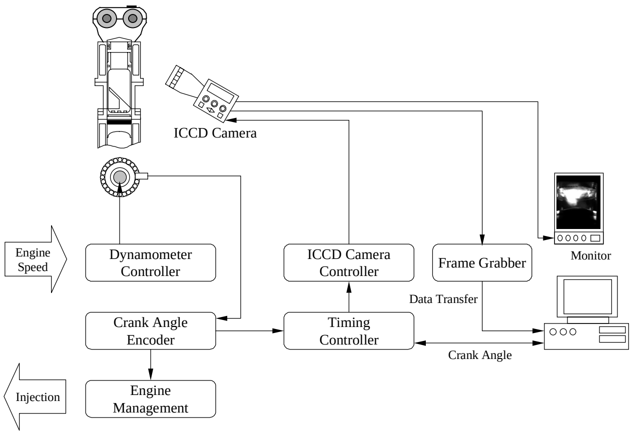


Figure 4. Photography of SCV and Injector position

Table 2 – Specifications of PDPA system

		Axial (Green)	Radial (Blue)
Light source		Ar-ion (5W)	
Laser beam dia.		1.4mm	
Wave length		514.5nm	488nm
Fringe spacing		3.2µm	3.1µm
Fringe number		36	
Beam waist dia.		117µm	111µm
Focal length	**Transmitter**	250mm	
	Receiver	250mm	
Collection angle		150°	

TEST CONDITIONS

A high-pressure swirl-type injector was applied here for gasoline direct injection engine application, which is a solenoid driven common rail type and has a tangential port. It is well known that this tangential port gives a higher angular velocity, thereby creating an air-cored vortex. Thus the rotating liquid flows through nozzle hole under both axial and radial forces to emerge from the injector in the form of a hollow conical sheet.

The injection flowrate was measured under 5, 6, and 7Mpa of injection pressure to survey fuel metering according to the variation of injection duration and to confirm a low-end linearity between the dynamic flow and fuel injection pulse width as well. Spray visualization was carried out at 5 and 7MPa of injection pressure and 3msec of injection pulse width. The spray mean drop size and mean velocity were measured at the center axis of fuel injection. In addition, the radial distribution of mean drop size and the mean drop velocity were also measured at 25 and 40mm from the injector tip as well. PDPA measurements were performed at 5 and 7MPa of injection pressure and 1msec of injection duration under room temperature and atmospheric pressure condition. For the investigation of in-cylinder spray flow motion, the single cylinder optical engine was operated at 1,000 and 2,000rpm under WOT condition. The fuel injection pulse width was set to 1.1msec for the homogeneous mixture and power operation mode. This is calibrated from pre-measured air and fuel injection flowrate.

RESULTS AND DISCUSSION

FUNDAMENTAL SPRAY CHARACTERISTICS

Injection flowrate

Figure 5 shows the effect of injection pressure on injection flowrate with different fuel injection pulse width. As the fuel injection pressure increases, the injection flowrate increases in accordance with the increase of fuel injection pulse width. The results indicate that the test injector has a good low-end linearity between the dynamic flow and fuel injection pulse width and the test injector is capable to the engine application.

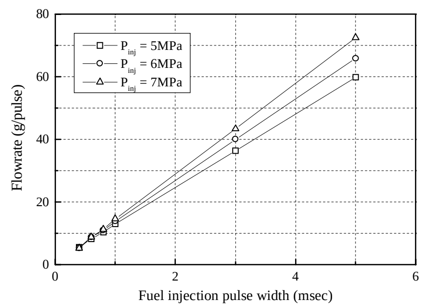


Figure 5. Effect of injection pressure on injection flowrate with different fuel injection pulse width

Spray developments and overall structure

The spray developments were visualized with respect to the elapsed times after injection under 5 and 7MPa of injection pressure as shown in Figure 6. The test section is 120mm(H)×94mm(V) and injection pulse width is 3msec.

It shows that this injector produces a hollow-cone spray, in which the most of the droplets are concentrated at the outer edge of a conical spray pattern. This is due to the centrifugal force by angular momentum generated at tangential ports in the nozzle. At 1.0msec after injection, upward spray vortex or the upward ring-shaped vortex on the spray surface region, which is headed opposite direction to the main spray, was beginning to shape because of pressure difference due to the relative velocity between the spray and ambient gas. As shown in the Figure 6, the increases of injection pressure lead to enhancement of the upward ring-shaped vortex on the spray outer surface. In this early injection stage, large and poorly atomized droplets are observed at the front of fuel injection due to the effect of injector sac volume. It has been reported that a large sac volume can significantly degrade the mixture formation process and can contribute to an increase in UHC emissions, especially for part load operation in which the sac volume may constitute a major fraction of the fuel required.

The cross-section view was captured at 30mm and 45mm downstream from the injector tip under 7MPa of injection pressure. In the case of 30mm downstream, the hollow-cone shape appears in the early injection stage but the spray pattern is changed to solid-cone spray at later stages. This is caused that the upward ring-shaped vortex introduces droplets into the inner side of the spray. At 40mm downstream from the nozzle exit, the solid-cone spray is become wider at later injection stages. It is thus estimated that the upward ring-shaped vortex contributed to the secondary atomization and uniform distribution of fuel droplets around the lower part of the spray.

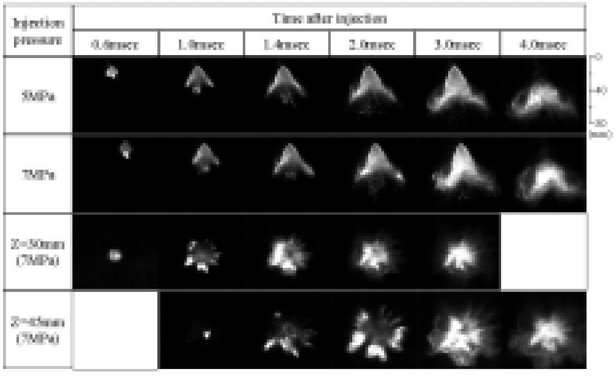


Figure 6. Spray developments and overall structure of the high-pressure swirl-type gasoline injector

Atomization characteristics

Figure 7 indicates the axial distribution of SMD and axial mean velocity at the center of injection axis under 5 and 7 MPa of injection pressure and 1msec of injection pulse width. SMD decreases to around 15mm downstream because of secondary atomization at both injection pressures. Then, SMD begins to increase to around 50mm downstream. This trend is due to the coalescence between the droplets in the peripheral and the ones in the inner region by upward ring-shape vortex as describe in Figure 6. As the axial distance moves to further downstream, the spray droplets are reduced because of floating droplets without injection pressure. it can be seen that the higher injection pressure generates relatively smaller droplets. In case of velocity distribution, it increases sharply up to 25 and 40mm and then decreases soon. These are due to the coalescence effect by the upward ring-shape vortex and aerodynamic drag force respectively.

Figure 8 shows the radial distributions of SMD and droplets velocity at 25 and 40mm from the nozzle tip. At 25mm downstream, as the radial distance increases, the droplet size increases, and reaches its highest value at 9mm radial position from the central axis of injection and then decreases. These trends represent that fuel spray is developed in the hollow-cone shape and larger droplets are concentrated on the outer edge of a conical spray pattern as illustrated in the spray visualization. However the droplet size at 40mm downstream shows the uniform distribution in radial direction. It is estimated that this is mainly caused by the effect of secondary atomization resulted from the upward ring-shaped vortex. According to the review of mixture preparation and combustion control for SI direct-injection gasoline engine by Zhao et. al. (1), the design goal of gasoline direct-injection engine fuel system should be to obtain a fuel spray of 25μm or less in SMD with good spray symmetry. Thus, It is assessed that the test injector is capable of GDI engine application.

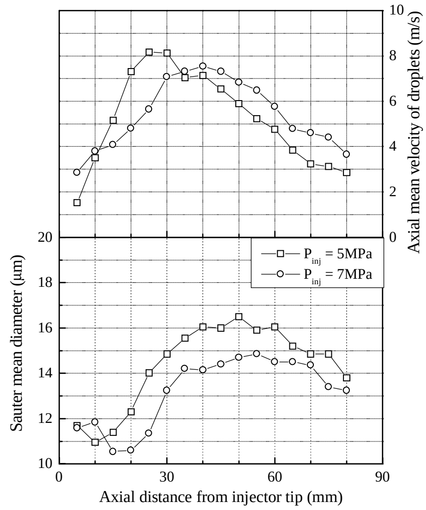


Figure 7. Axial distribution of SMD and axial mean velocity at the center of injection axis

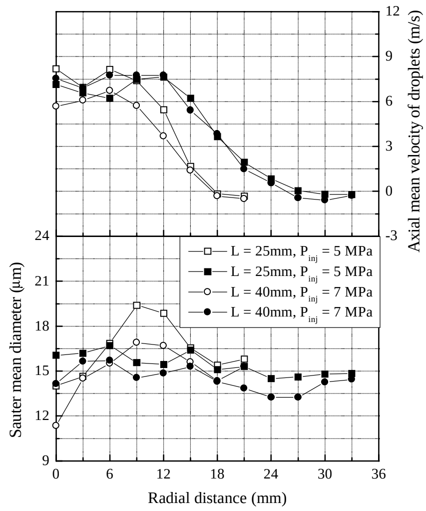


Figure 8. Radial distribution of SMD and axial mean velocity at different axial distance

IN-CYLINDER SPRAY FLOW MOTION

Figure 9 shows a characteristic sequence of fuel injection and mixture formation in GDI engine cylinder. The air-fuel ratio was controlled to homogeneous mixture for simulating a power operation mode at WOT and 1,000 rpm motoring condition. The fuel was injected at ATDC 90° CA during 1.1msec of pulse width under 7MPa of injection pressure. It can be seen that the fuel is injected up to ATDC 96° CA and the injected fuel is collided against the valve neck during the period. As observed at ATDC 100° CA, the piston type B makes a richer vapor region near the piston bowl. This is caused that the piston type B has smaller size of piston bowl and larger bottom

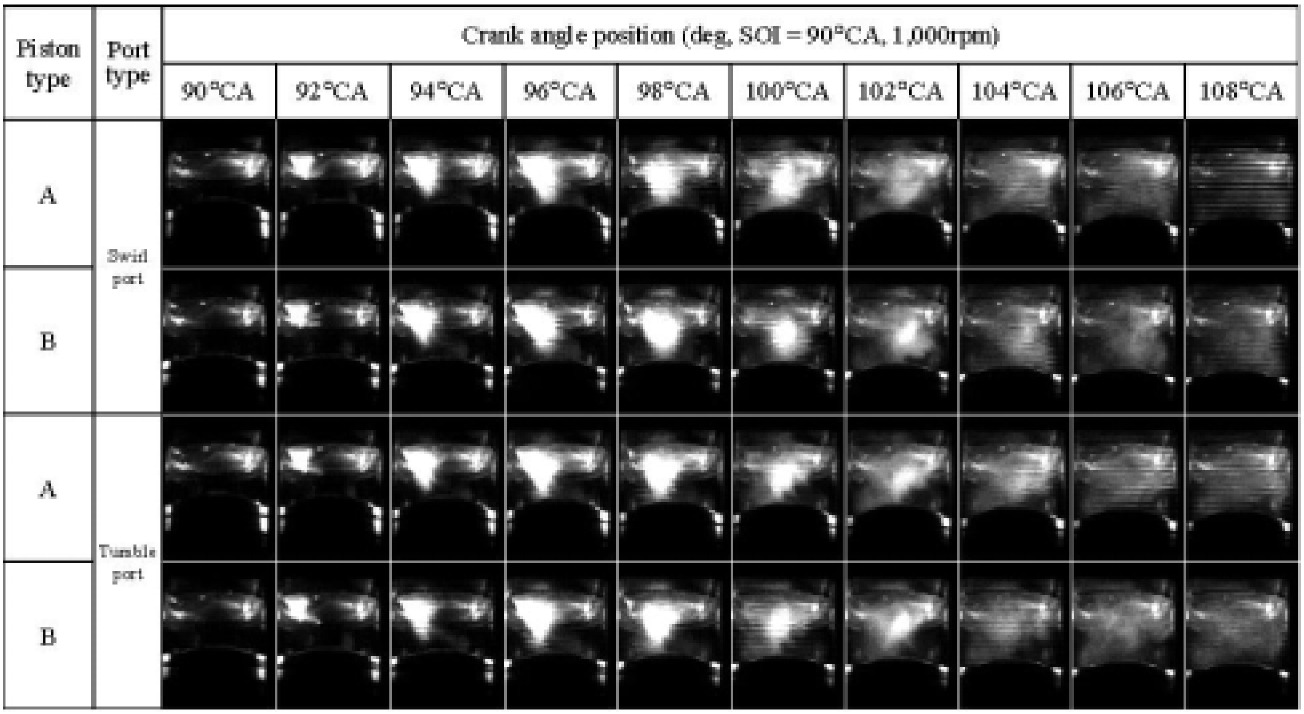


Figure 9 In-cylinder spray flow visualization at ATDC 90° fuel injection

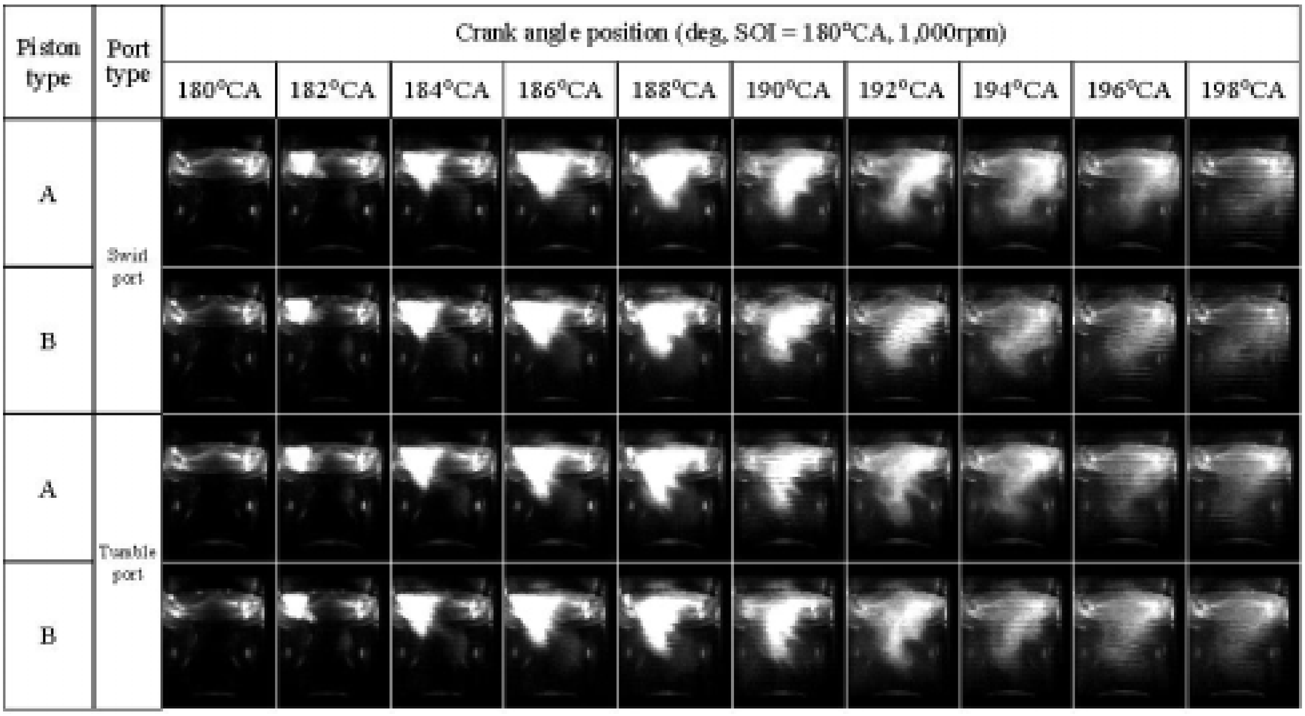


Figure 10 In-cylinder spray flow visualization at ATDC 180° fuel injection

curvature of the piston bowl than those of piston type A. And the spray tip penetration for the tumble port is found to be greater than that of swirl port. The spray for tumble port headed toward downward direction and dispersed somewhat widely comparing with swirl port. This is mainly due to the in-cylinder dominated tumble flow.

Figure 10 indicates a sequence of in-cylinder spray flow motion when the fuel is injected at ATDC 180° CA. For the tumble port, it can be obviously seen that the spray tip penetration is found to be greater than that of swirl port at ATDC 90° CA. This phenomenon becomes more dominant than that of ATDC 90° CA fuel injection case and the fuel spray is more dispersed in cylinder as the

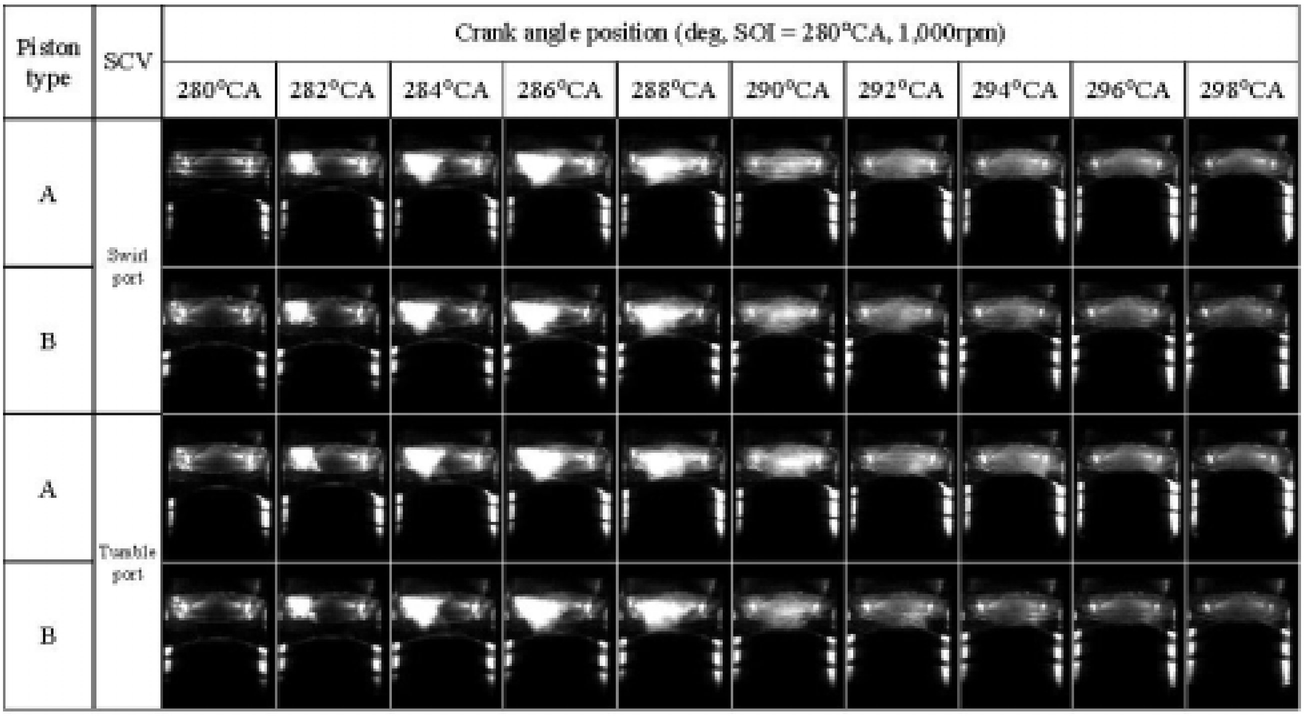


Figure 11 In-cylinder spray flow visualization at ATDC 280° fuel injection

piston moves to upward direction. It is thus estimated that the in-cylinder tumble flow is more effect on the formation of homogeneous mixture than that of in-cylinder swirl flow at early injection mode.

In the case of late injection, the injected fuel spray forms the rich-vapor region inside cylinder at ATDC 290° CA comparing with above two injection cases. And this is head to combustion chamber by the in-cylinder swirl flow as shown in Figure 11. It is thus considered that the in-cylinder swirl flow plays a better role of stratified mixture preparation than tumble flow at late injection mode.

CONCLUSION

An experimental study of the detailed spray characteristics and the in-cylinder spray flow motion has been analyzed to optimize mixture formation process in the development stage of mass production GDI engine. Based on the information obtained by experimental results, the following conclusions were reached.

- The test injector has a good low-end linearity between the dynamic flow and injection pulse width and fuel spray of 20μm or less in SMD with good spray symmetry. It is thus estimated that the test injector is capable to the engine application.

- For the early injection mode, the in-cylinder tumble flow is more effect on the formation of homogeneous mixture than that of in-cylinder swirl flow. It is also considered that the in-cylinder swirl flow plays a better role of stratified mixture preparation than tumble flow at late injection mode.

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