286 *KSME International Journal, Vol. 13, No. 3, pp. 286~293, 1999*

A Study on Fuel Spray of Spark-Ignited Direct Injection Engine Using Laser Image Technology.

Nae Hyun Lee,* Jong Ho Park* and Kyu Hoon Choi*

(*Received July 6, 1998*)

One of the important research for developing a spark-ignited direct injection engine is optimization of the fuel spray distribution and air flow field in the cylinder. Therefore, spray pattern and mean fuel droplet size of swirl injector were investigated using Laser Light Sheet Photography and PDPA' respectively. And, for the formation of stratified mixture with adequate strength near a spark plug at injection mode in compression stroke, spray distribution after impingement on flat piston or bowl piston in a transparent motoring engine was visualized for the three different injector positions. .

Key Words : Spark-ignited Directed Injection(SDI), Swirl Injector, Phase Doppler Particle Analyzer(PDPA), Sauter Mean Diameter(SMD), Penetration, Transparent Single Cylinder Engine, Spray Impingement

1. Introduction

SDI(Spark-ignited Direct Injection) engine has been regarded as one of the most promising technologies for better fuel economy. Recently, with a high pressure injection system based on common rail concept, to control injection timing and even injection pressure are easily realized with greater flexibility(Iwamoto et al., 1997 ; Harada, 1997 and Fraidle et al., 1996). Also, excellent fuel atomization has become possible due to the development of a high pressurized swirl-generating hollow cone injector.

In most cases, SDI engines use two stage injection strategy(Lai et al., 1997 ; Tomita et al., 1997) : late injection mode for stratified charge combustion at partial load and early injection mode for homogeneous charge combustion at full load. However, the required spray characteristics are quite different in each case. While well dispersed fuel spray is desirable to ensure homogeneous mixture in the early injection mode, well atomized compact spray is preferable to achieve rapid mixture formation and controlled stratification in the vicinity of a spark plug in the late injection mode(Ando et al., 1996, Lake et al., 1996). Therefore, for developing a SDI engine, first of all, spray characteristics such as penetration, spray angle and fuel pressure should be optimized not only for minimizing the wall wetting but also for enhancing the atomization. Next, placing an injector at optimum position might be sufficiently reviewed because there exist problems such as injector tip temperature, fouling of spark plug and injector, and design constraints for injector access and maintenance. In addition, in-cylinder fuel/air mixing should be followed by combustion control strategies.

Kia has been working on SDI engine for years, and many fundamental researches related to SDI have been being conducted(Lee et al., 1998 and Shin, 1997). So, in the present paper we show the results of our work focussed on spray characteristics including spray visualization taken by Laser Light Sheet Photography and SMD(Sauter Mean Diameter) distribution measured by PDPA (Phase Doppler Particle Analyzer). In addition, spray motion behavior after impingement on piston top geometry for different injector locations using transparent engine is shown.

---

* KIA Motors Corp.

2. Spray Characteristics of Swirl Injector

2.1 Injection System and Experimental Apparatus

In order to realize accurate injection timing and quantity control, the needle type electromagnetic injector shown in Fig. 1 was selected. It is approximately the same size as the conventional injectors for port injection. This injector has a swirl channel upstream of the needle, which is designed to have 45° main axis intersection between the flow vector and the nozzle axis, and generates a hollow cone spray. A rotational momentum is given to the fuel droplets by a swirler channel.

Fuel is pressurized by a conventional low fuel feed pump from the fuel tank and supplied to the high pressure pump. It returns to the tank by an overflow bypass valve. Fuel pressure in the high pressure line is controlled as high as 120 bar by the high pressure regulator. And injection quantity and timing of the high pressure injector is controlled by a pulse signal from ECU to injector drive unit. N-Heptane was used as a test fuel. A high pressure fuel supply system is shown in Fig. 2.

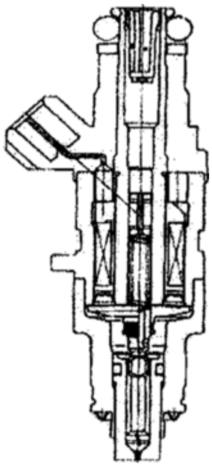


Fig. 1 Swirl injector.

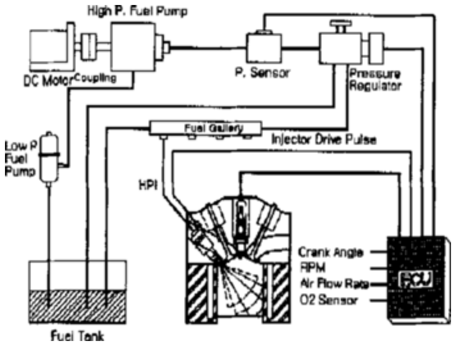


Fig. 2 High pressure fuel supply system.

Configuration of the experimental apparatus to characterize the spray is shown in Fig. 3. To visualize spray pattern, Nd : YAG laser with 10 ns pulse width and a digital CCD camera were used. Circular laser beam emitted from laser exit hole was transferred by an articulated arm type optical linkage to the cylindrical and spherical lens, which produce a sheet beam of thickness 0.2 mm at measuring test plane. Also, to measure the droplet size and velocity, continuous Ar-ion laser based PDPA (Phase Doppler Particle Analyser) was used. The focal length of used lens is 500 mm for the transmitter and 300 mm for the receiver' respectively. Variations of spray characteristics test are shown in Table. 1

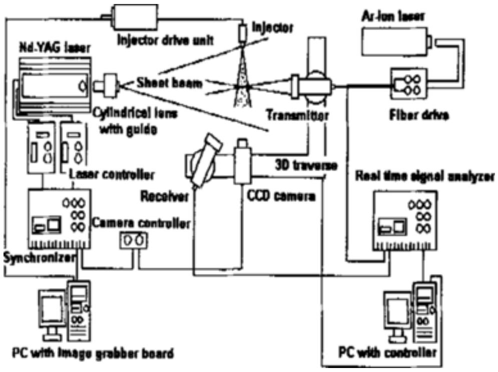
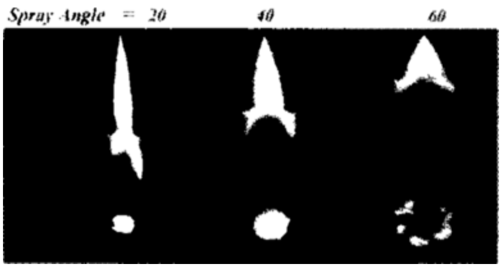


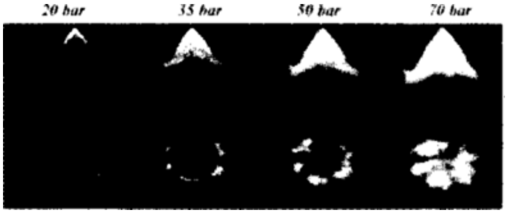
Fig. 3 Schematic diagram of experimental apparatus (Laser Light Sheet & PDPA).

Table 1 Variations of spray characteristics test.

Injector spray angle	20°, 40°, 60°
Injection pressure (bar)	20, 35, 50, 70
Injection duration (ms)	1, 10
Ambient pressure	Atmospheric pressure



(a) Spray change depending on cone angle (injection pressure=50 bar).



(b) Spray change depending on injection pressure(cone angle=60°).

Fig. 4 Spray structure of swirl injector(at t=2 ms after SOI, injection duration 10ms).

2.2 Spray structure in quiescent condition

Figure 4 (a) shows the variation of spray structure with the change of spray angle of the swirl injector. These pictures were taken at 2 ms after injection start with injection pressure 50 bar and injection duration 10 ms. Horizontal sectional view is at Z=30mm down from the injector tip' and vertical sectional view at the central section of the injector tip. With a larger spray angle, spray penetration becomes shorter' but spray dispersion becomes wider and a ring vortex is shown near the injector nozzle tip. From the picture of the spray structure at a horizontal sectional view, fuel distribution for a spray angle of 20° appears much concentrated because air entrainment into the spray is more difficult. On the contrary, for the spray angle of 40°, fuel distribution of the outer region is shown with lower density. This means that air is entrained into the spray easily so as to transfer the heat from the surroundings and make the droplets atomized. For the spray angle of 60°, spray is fully developed into a hollow cone shape with sufficient air entrainment. In addition, the hollow cone spray shows the six-divided discrete spray plume.

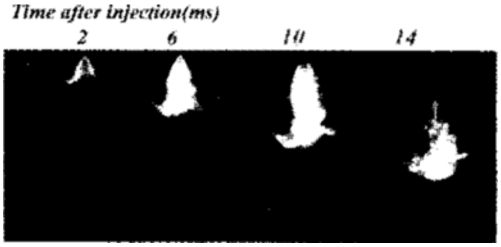


Fig. 5 Time hisrory of spray structure.

Figure 4(b) shows variation of the spray structure with the change of injection pressure for the spray angle of 60°. Both in horizontal and vertical sectional views, the injection rate becomes higher with the high injection pressure and it results in denser droplet distrbution. And, as spray penetration with higher injection pressure becomes longer without changing the spray shape, more droplets can meet the surrounding air. Therefore, assuming no impingement on the wall, injecting optimum quantity with higher pressure at the a fixed load condition seems to enhance the droplet atomization and shorten the injection duration. Consequently, allowable mixing period might be increased and the formation of homogeneous mixture might be improved.

Figure 5 shows a time history of the spray structure for the spray angle of 60° and injection pressure of 50 bar. After fuel injection is finished, the spray penetration velocity becomes slower and even droplets at downstream continue to meet air and be atomized. Then, the size of the ring vortex playing a role to enhance atomization and mixing continues to increase untill fuel injection is finished

2.3 Distribution of mean droplet size and velocity

Measuring points were at the horizontal sections of Z=10, 30, and 60 mm axial direction down from the injector tip. And the radial position at each horizontal section was determined considering outer boundary of spray. The frequency and duration of injection are 12.5Hz and 1 ms respectively which are equivalent to those of 1500 rpm, 1.5 bar BMEP load condition. Around

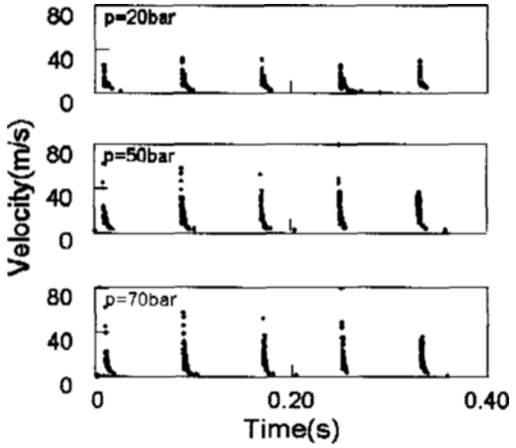


Fig. 6 Spray velocity as a function of time at various injection pressures.

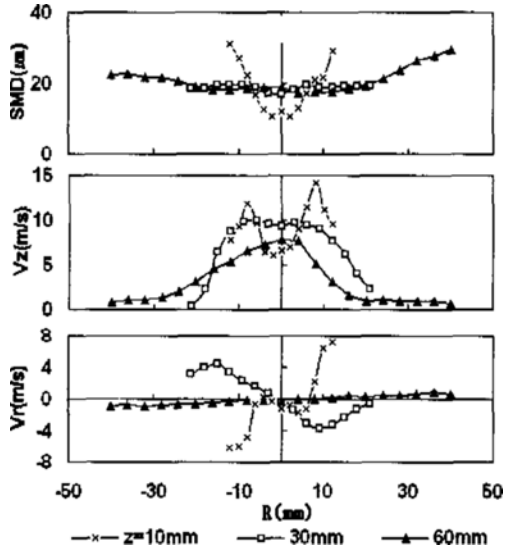


Fig. 7 Radial distribution of SMD and velocity at various measuring positions.

1000~3000 data were sampled and analyzed at each point for measuring SMD, axial and radial components of mean velocity.

The fluctuation of pressure in the fuel line is expected as the most dominant factor on a cycle variation when quantifying the spray characteristics. Fig. 6 shows the sampled injection rate for the three injection pressure cases. From these results, it is found out that comparable stable injection at each cycle condition can be acquired by using common-rail type high pressure fuel injection system with good pressure control functionality.

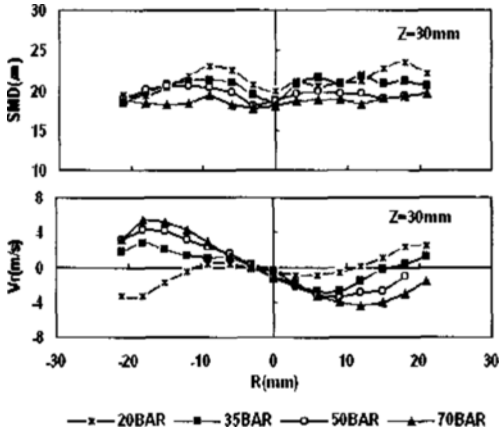


Fig. 8 Radial distribution of SMD and velocity at various injection pressures.

Figures 7 and 8 show SMD and spray velocity according to the measuring position and injection pressure. At upstream position of spray ($Z=10$ mm), large droplets existed near the main stream and less fuel droplets are induced into the central area. However, the farther the measuring point is from the injector tip, the more uniform the distribution of SMD and droplet velocities become. This is due to the strong mixing with induced air. Also, air entrainment by a swirl motion is clearly shown from the fact the direction of radial velocity at $Z=30$ mm is opposite to the direction of radial velocity at $Z=10$ mm. SMD at any position in a swirl injector is within the size of 15~30 μm and become about 20 μm size uniformly at 30 mm downstream of the injector tip. And with higher injection pressure, SMD becomes smaller and radial velocity which is related to the air entrainment becomes higher. Then, the higher injection pressure leads to a more sufficient mixing opportunity due to the decreased spray size and higher air entrainment.

2.4 Change of spray structure depending on ambient pressure

Figure 9 shows the development process of the spray structure depending on ambient pressure. And Fig. 10 shows the penetration and dispersion of each case. Spray at 5 bar condition also has a ring vortex structure, which is a unique character-

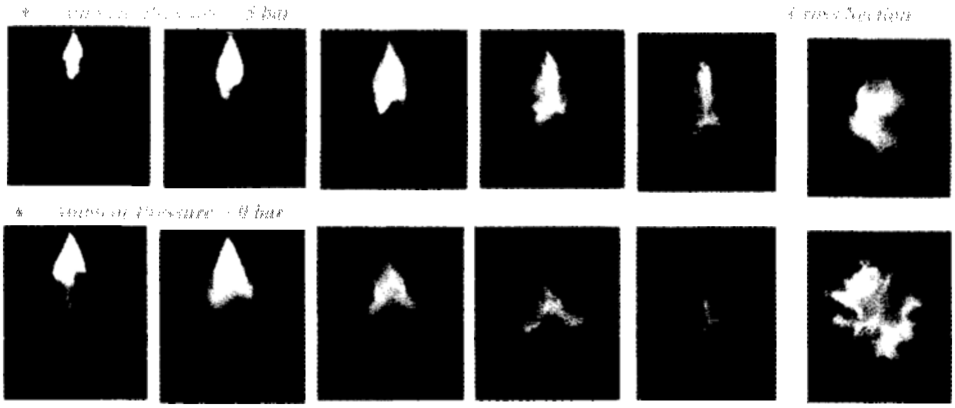


Fig. 9 Dependence of spray distribution on ambient pressure.

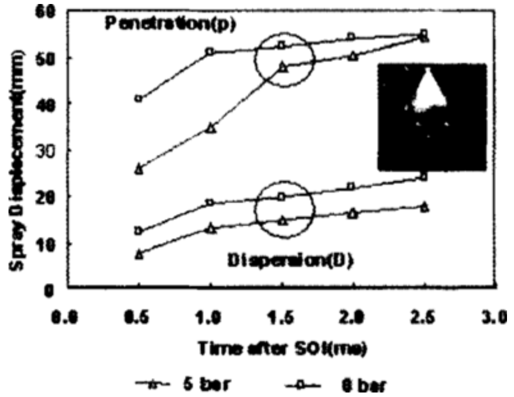


Fig. 10 Dependence of spray penetration and dispersion on ambient pressures.

istic of a swirl injector, but has comparatively a narrow spray angle and is not fully developed into the hollow cone shape. This results from the increased aerodynamic drag on the droplets. At the atmospheric pressure condition, the penetration rate is rapidly decreased while the dispersion rate is still maintained to 1 ms after end of the injection. The penetration rate under a higher ambient condition is lower than that of the under atmospheric condition. The controlled spray structure under a higher ambient condition enables injection in a compression stroke to produce the stratified mixture. And design of the piston shape and bowl size in this study was investigated by analyzing characteristics and formation process of the spray.

Table 2 Engine specifications and operating conditions.

Bore* Stroke	81 mm*87 mm
Valves per cylinder	4(DOHC)
Compression Ratio	11 : 1
Intake Valves : Max. lift	7.6 mm
Engine speed	600~800 rpm
Intake Valve Timing	Open : 6 BTDC Closed : 46 ABDC

3. Spray Impingement on Piston in a Transparent Engine

3.1 Transparent single cylinder engine

The single cylinder research engine is based on a standard commercial kit version and was modified to accommodate a prototype cylinder head of four valve pentroof geometry. The operating characteristics of this engine are summarized in Table 2.

In order to visualize in-cylinder spray behaviair, engine was modified for optical access through quartz liner and piston window. In addition, a flat piston window was replaced with the opaque piston adapter having bowl-shaped top face to examine the influence of piston top geometry on spray impingement and in-cylinder flow.

3.2 In-cylinder spray distribution after impingement on the piston

Figure 11 shows the experimental apparatus to visualize in-cylinder spray pattern using a transparent signle cylinder engine. The purpose of spray visualization in a transparent engine is to observe the process of spray impingement in a vertical sectional view as well as spray distribution in a horizontal sectional view. In these experiments, the revolution speed of engine is 800 rpm and injection duration is 1 ms equivalent to that of the practical engine. Spray picture was taken from 0.5 ms after SOI to 2.5ms by 0.5ms step.

Figure 12 shows the configurations of three different cylinder heads to determine optimum injector location and port geometry. In all cases, a spark plug is located at the central position of the combustion chamber to minimize modifying base cylinder head. But, the injector location of the left figure is at the central position near the spark plug (central injection) and for the center figure is between the intake valve and the exhaust valve (side injection). And, the layout of these two cylinder heads is aimed at utilizing the conventional tumble flow without modifying the geometry of base intake port considering common use of manufacturing facilities. Finally, in case of the right figure, injector is located between two intake valves (intake side injection) and top entry intake port is also used.

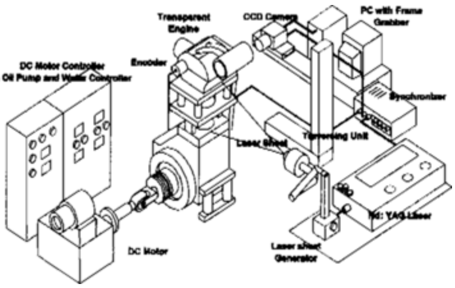


Fig. 11 Experimantal appartus to visulize in-cylinder spray pattern using transparent engine.

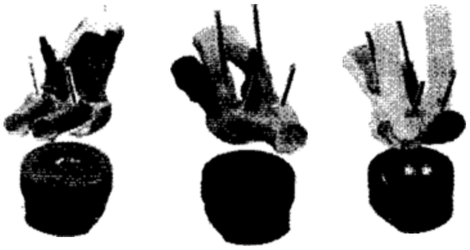


Fig. 12 Cylinder head configurations.

Figures 13 and 14 show the pictures of impinged spray behavior on flat piston in central injection and side injection when SOI is at BTDC 60° in a compression stroke. Since impinged spray of central injection is concentrated on central area of combustion chamber, the bowl located in piston center allows well-controlled stratification to produce even extremely lean mixture overall. But since main stream of impinged spray goes toward spark plug, mixture formation could be very sensitive to the spray characteristics and not be assisted with bulk flow in a tumble air flow system. On the contrary, considering the traveling path of the impinged spray in side injection, the adequate distance from injector to the spark plug through an impingement point of piston is in favor of increasing allowable time for atomization and evaporation. But, since travelling direction of spray is perpendicular to the direction of

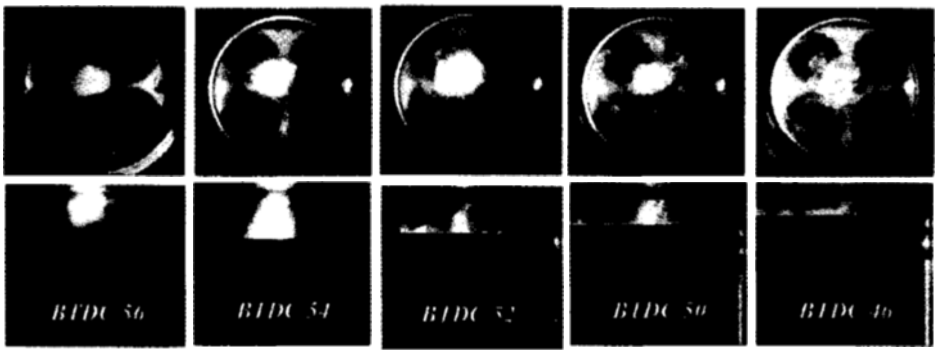


Fig. 13 Behaviour of spray impingement on flat piston in central injection.(SOI : BTDC 60).

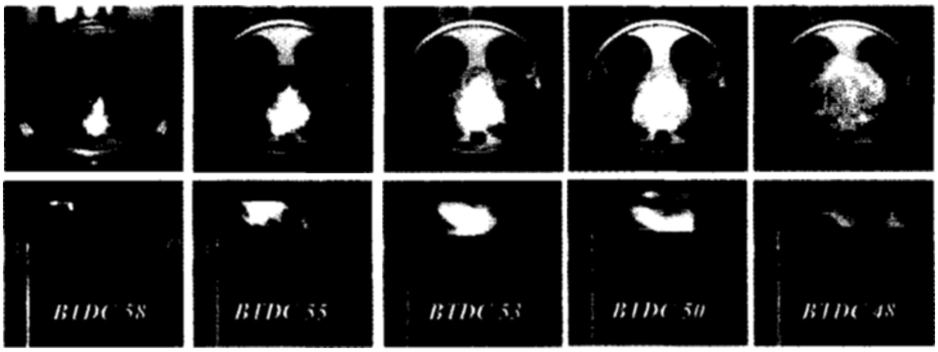


Fig. 14 Behaviour of Spray impingement on flat pistion in side injection. (SOI : BTDC 60).

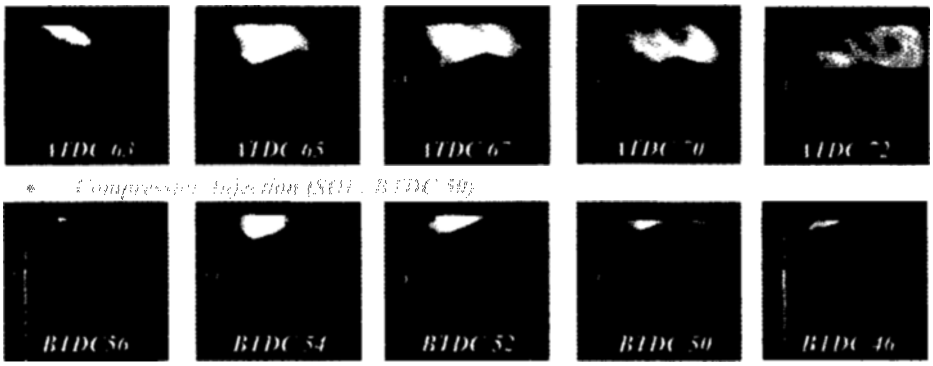


Fig. 15 Behavior of spray impingement on bowl piston in intake side injection.

tumble air flow, spray distribution could be disturbed by air flow and unprofitable for stable stratification. Therefore, intake side injection with bowl shaped piston would be better for the formation of stable stratified mixture in the vicinity of spark plug. Also, the bulk air flow motion also should be optimized.

Figure 15 shows the behaviour of spray impingement on bowl piston in intake side injection. In this study, bowl shaped piston and top entry intake port was used on the basis of above precedeed experimental results. Distributed spray after impingement is well trapped into the piston bowl. And it is moved to the spark plug by weak counter rotating tumble (rotating direction of which is opposite to the rotation of conventional tumble, in some papers called as reverse tumble) generated from the top entry intake port. But, operating range of SOI was too limited to be usuable for the stable stratified operation at high speed range above 2000 rpm. Therefore, injector spray angle, size and shape of piston bowl, injection timing should be matched through the combustion experiments for the wide range of stable stratified operation.

4. Summary

Fundamental researches to investigate spray characteristics of the swirl injector and the spray behaviour after impingement on the piston in three different injector locations were carried out. From these studies, the following results were obtained.

(1) A wider spray angle leads to increased contact area with air due to the increased spray dispersion. And a higher injection pressure leads to the a more sufficient mixing opportunity due to decreased SMD and the shorter injection duration with higher injection rate. Therefore, both the wider spray angle and the higher injection pressure contribute to the favorable homogeneous

mixture formation.

(2) SMD of swirl injector under atmospheric temperature condition is within the size of 15～30 μm. From the droplet velocity and size measurement of swirl injector, the fact that air is induced strongly into a spray and droplet size become small and uniform was found out.

(3) Spray of swirl injector has a ring vortex structure, which is generated by strong air entrainment into a spray. Spray under high ambient pressure has compact shape suitable for stratified mixture, and has still ring vortex structure suitable for atomization and mixing even though spray is not fully developed into hollow cone shape.

(4) Spray distribution after impingement on the flat or bowl piston in a transparent engine was visualized for the three different injector positions. From these studies, intake side injection seems to be most favorable for the stratified mixture formation with adequate strength near the spark plug at a injection mode in a compression stroke.

Reference

Iwamoto, Y., Noma, K., Nakayama O. and Ando, H., 1997, "Development of Gasoline Direct Injection Engine," *SAE* Paper No. 970541.

Harada, J., Tomita, T., and Mizuno, H., Ito, Y., 1997, "Development of Direct Injection Gasoline EngVaine," *SAE* Paper No. 970540.

Fraidle, G. K., Piock, W. F., and Wirth, M., 1996, "Gasoline Direct Injection ; Actual Trends and Future Strategies for Injection and Combustion Systems," *SAE* Paper No. 960465.

Lai, M., Zhao, F. and Harrington, D., 1997, "A Review of Mixture Preparation and Combustion Control Strategies for Spark Ignited Direct Injection Gasoline Engines," *SAE* Paper No. 970627.

Tomita, T., Sasaki S. and Sawada, D., 1997, "Development of Direct Injection Gasoline Engine Study of Stratified Mixture Formation," *SAE* Paper No. 970539.

Ando, H., Kume, T., Iwamoto, Y. and Murakami, M., 1996, "Combustion Control Technologies for Direct Injection SI Engine," *SAE* Paper No. 960600.

Lake, T. H., Sapsford, S. M and Stokes, J., "Simulation and Development Experience of a Stratified Charge Gasoline Direct Injection Engine," *SAE* Paper No. 962014.

Shin, M. K., Park, J. H., Lee, N. H. and Choi, K. H. and 1997, "A Study on the Spray and Combustion Characteristics of Gasoline Direct Injector," *KSAE Transaction* Vol. 5 No. 5, pp. 114～122.

Lee, N. H., Yu, C. H. and Choi, K. H., 1998, "A Study on the Developement of Stoichiometric Direct Injection Gasoline Engine by Homogeneous Charge," *KSAE Transaction* Vol. 6 No. 2, pp. 32～42.