International Journal of Automotive Technology, Vol. 2, No. 4, pp. 165–170 (2001)

1229–9138/2001/006–05

SPRAY STRUCTURE OF HIGH PRESSURE GASOLINE INJECTOR IN A GASOLINE DIRECT INJECTION ENGINE

Chang Sik Lee[1], Mun Soo Chon[2)*] and Young Cheol Park[3]

[1]Department of Mechanical Engineering, Hanyang University, Seoul 133-791, Korea
[2]Technical Center, Daewoo Motor Co., Ltd., Incheon 403-714, Korea
[3]Department of Automotive Engineering, Shinsung College, Chungnam 343-860, Korea

(Received 10 June 2001)

ABSTRACT–This study is focussed on the investigation of spray characteristics from the high pressure gasoline injector for the application of gasoline direct injection engine. For the analysis of spray structure of high pressure gasoline injector; the laser scattering method with a Nd-Yag laser and the Phase Doppler particle analyzer system were applied to observe the spray development and the measurement of the droplet size and velocity of the spray, respectively. Also spatial velocity distribution of the spray droplet was measured by use of the particle image velocity system. Experimental results show that high pressure gasoline injector shapes the hollow-cone spray, and produce the upward ring shaped vortex on the spray surface region. This upward ring shaped vortex promotes the secondary atomization of fuel droplets and contributes to a uniform distribution of fuel droplets. Most of fuel droplets are distributed under 31 μm of the mean droplet size (SMD) and the frequency distribution of the droplet size under 25 μm is over 95% at 7 MPa of injection pressure. According to the experimental results of PIV system, the flow patterns of the droplets velocity distribution in spray region are in good agreement with the spray macroscopic behaviors obtained from the visualization investigation.

KEY WORDS : Spray structure, High-pressure injection, Phase Doppler particle analyzer, Sauter mean diameter

1. INTRODUCTION

In recent years, the restriction on the exhaust emissions from the automotive engines such as unburned hydrocarbons (UHC), CO, and NOx becomes more stringent. In addition, the carbon dioxide (CO_2) from the automotive engines is an important environmental problem because the exhaust emissions of the vehicles have an effect on the increase of greenhouse gas. Gasoline direct injection engine has great potential to reduce these hazardous exhaust emissions and to postpone the exhaustion of fossil fuel (Zhao *et al.*, 1997). The spray characteristics of the direct injection engine such as the mean drop size, spray tip penetration, velocities and spray cone angle have influence upon the air-fuel mixing rate, the distribution of mixture concentration and the wetting of cylinder liner and piston head. The spray characteristics and spray structure in the direct injection engine have important role in the improvement of engine performance and the reduction of emissions. Thus a substantial understanding of global spray structure and quantitative characteristics of spray are decisive to optimize the exhaust emission control of direct injection gasoline engine (Yoo *et al.*, 1997; Iwamoto *et al.*, 1997). The spray evolution processes and characteristics in the direct injection gasoline engine based on experimental visualization have been reported by many researchers (Lee *et al.*, 1997; Zhao *et al.*, 1999; Lee *et al.*, 2001).

The results of previous investigation by many researchers were provided the detailed characteristics of fuel spray but there are still much uncertainty about spray evolution and mixing behavior of the fuel spray in the direct injection gasoline engine.

The objective of this paper was to investigate the spray evolution with respect to time, spray tip penetration, spray shapes, and upward counterpart vortex by the ambient air-entraining phenomenon of high-pressure gasoline injector. In order to obtain the spray characteristics of high-pressure gasoline injector, this study deals with the mean droplet size distribution, axial velocity of droplets, and the other spray characteristics.

Corresponding author. e-mail: cslee@hanyang.ac.kr

2. EXPERIMENTAL APPARATUS AND PROCEDURES

Figure 1 shows the schematic diagram of high-pressure injection and Phase Doppler particle analyzer (PDPA) systems. The high-pressure injection system consisted of

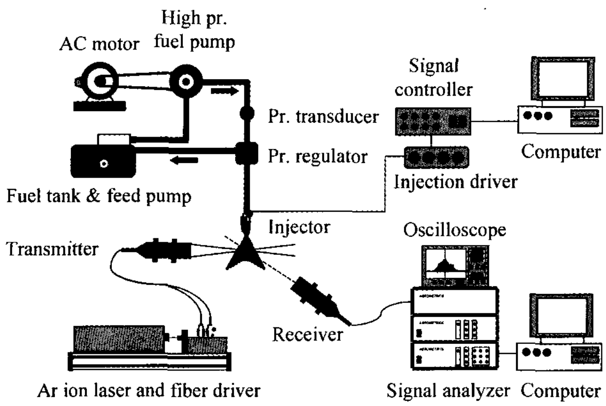

Figure 1. Schematic diagram of high pressure injection with PDPA system.

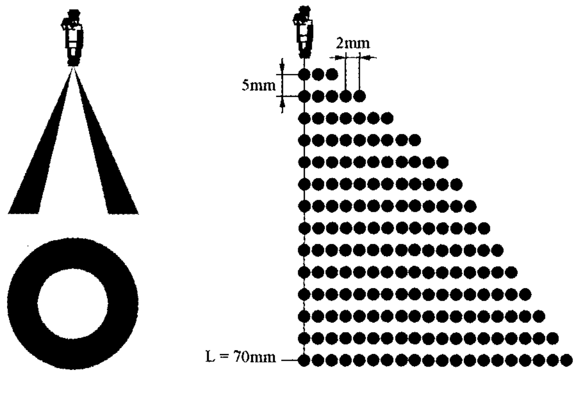

Figure 2. Hollow-cone spray produced by high-pressure swirl injector test points of PDPA measurements.

a fuel feeding pump, high-pressure pump, pressure regulator and piezoelectric pressure sensors. The high pressure fuel pump and the pressure regulator with the piezoelectric pressure sensors were utilized to adjust fuel injection pressure, and injection timing was controlled by the signal controller.

The PDPA system was used to measure the overall droplet size, axial mean velocity, and particle distribution. The specifications of PDPA system were listed on Table 1.

Spray vis●ilization was also conducted by employing the laser light scattering method with a Nd-Yag laser and CCD camera. The fuel injection timing and injection duration signals are controlled by the computer system and these signals are delivered to the injector via signal controller and injection driver. For the synchronization of the injection signal, laser pulse and CCD camera, the injection signal was used as an input signal to laser pulse synchronizer and the frozen image of the fuel spray was captured onto the image grabber from the CCD camera with 50 mm lens.

In this experiments, proto-type high pressure swirl injector, which has 0.6 mm diameter single hole with four tangential ports, was used. It was well known that these tangential ports give 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 hollow conical sheet. Figure 2 shows the hollow-cone spray produced by the high-pressure swirl injector and test points of PDPA measurements.

The phase Doppler method can provide a good velocity information of liquid droplets but it is insufficient to investigate velocity field overall spray regions simultaneously. This problem can be overcome by applying the PIV system to measure spatial distribution of droplet velocity.

Figure 3 shows the schematic diagram of the PIV system and the specifications of PIV system are listed in Table 2. The cross-correlation technique from two sequential images was utilized to remove the ambiguity of velocity direction in the spray flow field. And the interrogation section for obtaining one velocity vector

Table 1. Specifications of PDPA system.

Wave length	514.5 nm, 488 nm
Laser beam diameter	1.4 mm
Fringe spacing	3.214 μm, 3.090 μm
Fringe number	36
Beam waist diameter	116.979 μm, 110.954 μm
Focal length	250/500 mm for transmitter 250 mm for receiver
Collection angle	30°

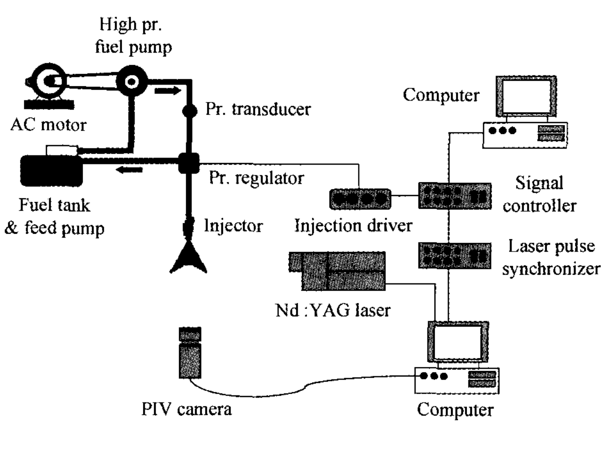

Figure 3. Schematic diagram of PIV system.

Table 2. Specifications of PIV system.

Laser source	Nd:YAG (Q-switched)
Wave length	532 nm
Laser power	12 mJ
Beam thickness	~1.0 mm
PIV camera	1,028 × 1,028 pixels
Frame interval	4 μsec
Interrogation section	64 × 64 pixels (with 50% overlap)

was 64 × 64 pixels with 50% overlap region.

3. RESULTS AND DISCUSSIONS

3.1. Development of Global Spray

Figure 4 and 5 show the spray development of high-pressure gasoline injector at the various elapsed times after injection under 5 and 7 MPa injection pressures respectively. As shown in these figures, it could be observed obviously that this injector produces a hollow-cone spray, in which 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 0.8 msec

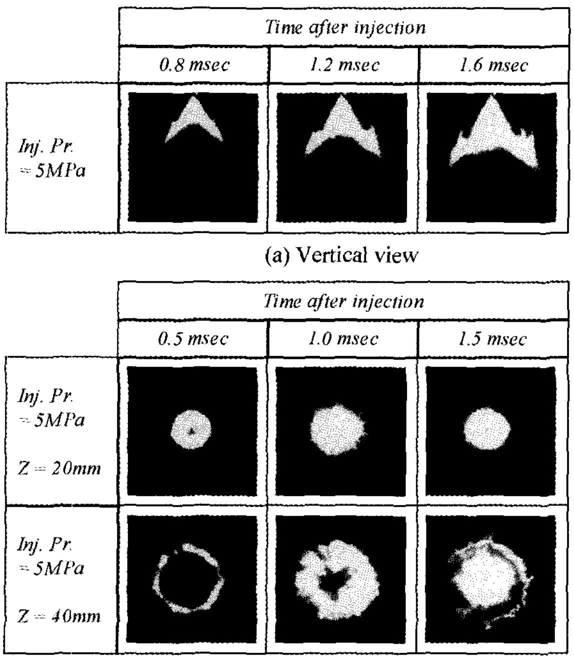

Figure 4. Spray developments of high-pressure gasoline injector at 5 MPa of injection pressure.

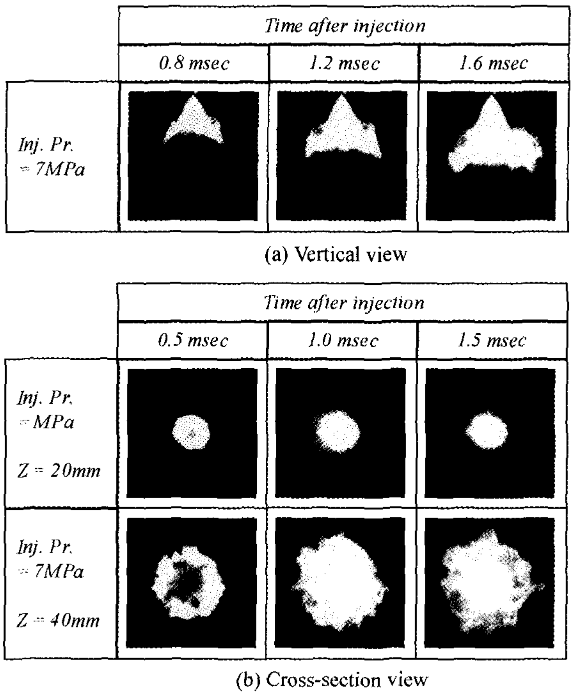

Figure 5. Spray developments of high-pressure gasoline injector at 7 MPa of injection pressure.

after injection, 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 noted by Lee *et al.* (Zhao *et al.*, 1999) the increase in injection pressure has played an important role in the increase of upward ring shaped vortex on spray outer surface. As the time increased, the upward ring shaped vortex on the hollow-cone spray is more increased in accordance with the elapsed time. In the case of cross-section view, the hollow-cone shape appears in the early injection stages but this spray pattern is changed to solid-cone spray pattern at later stages because the upward ring shaped vortex introduces droplets into the spray inner side as shown in these figures. It is thus estimated that this upward spray vortex contributed to a uniform distribution of fuel droplets.

3.2. Atomization Characteristics

Figure 6 indicates the radial distributions of Sauter mean diameter (SMD) at 20, 40 and 60 mm downstream from nozzle tip at 7MPa of injection pressure. In this figure, SMD is the mean diameter of droplets, which is defined as the ratio of volume to surface area of the total sample droplets.

As the radial distance increases, the SMD also increases rapidly at the 20 mm downstream, reaches its

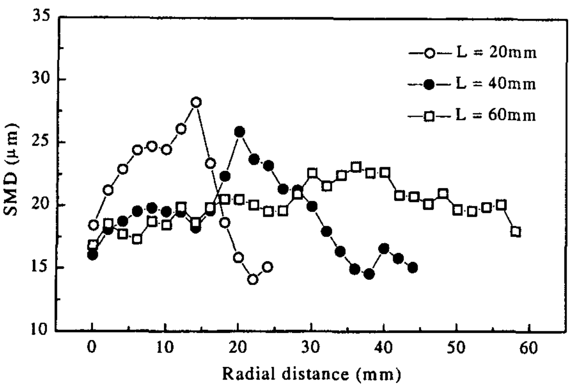

Figure 6. Spray developments of high-pressure gasoline injector at 7 MPa of injection pressure.

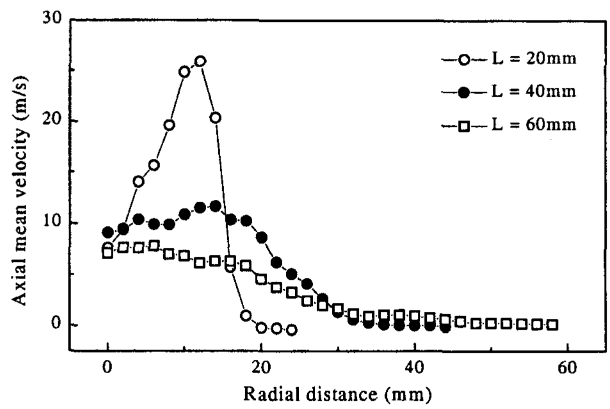

Figure 7. Radial distribution of axial mean velocity at different axial distance.

highest value of 28.2 μm at 14 mm radial position from the central axis of injection nozzle and then decreases steeply. At 40 mm downstream, the radial distributions of mean drop size are similar to the distribution at 20 mm downstream but the highest value of SMD is measured 25.9 μm at 20 mm radial position from central axis of injection. The results of SMD measurement are similar to the results of previous studies by Lee *et al.* (2001) and and Zhao *et al.* (1999). 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.

Comparing to the radial direction at 20 mm, 40 mm downstream, the SMD at 60 mm downstream show the uniform distribution. This is caused by the effect of secondary atomization resulted from upward ring shaped vortex. Thus, it is confirmed that upward ring shaped vortex has an important role in fuel atomization and uniform distribution of droplets.

Radial distributions of axial mean velocity at 20 mm, 40 mm and 60 mm downstream from nozzle tip were shown in Figure 7. Radial distributions of axial mean velocity have similar aspects to radial distributions of SMD. It was found that the larger droplets at the upper spray region flow along the out side of spray cone because of upward ring vortex on the spray cone surface. According to the result of mean velocity, the downward velocity at inner side is higher than that of outer side due to the upward ring shaped vortex.

Figure 8 show the droplets velocity and SMD distribution, which were measured by PDPA system. At upstream of spray, large droplets with high velocity are flows to the downstream and this large momentum is disappeared at downstream, which is due to upward ring shaped vortex as discussed above.

It is clear that the upward ring shaped vortex promotes the secondary atomization of fuel droplets and contri-

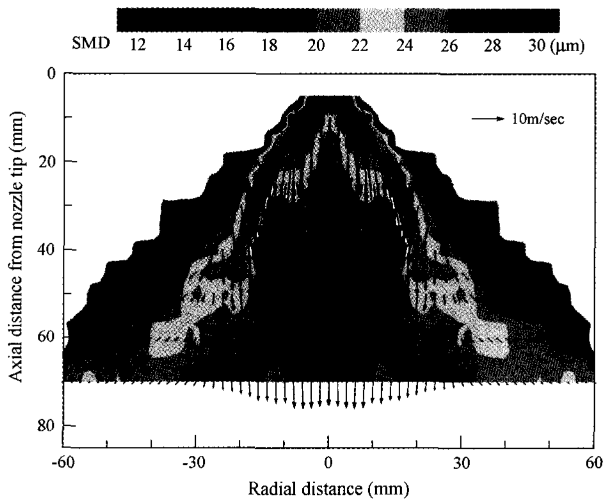

Figure 8. SMD and vector field of high pressure gasoline injector.

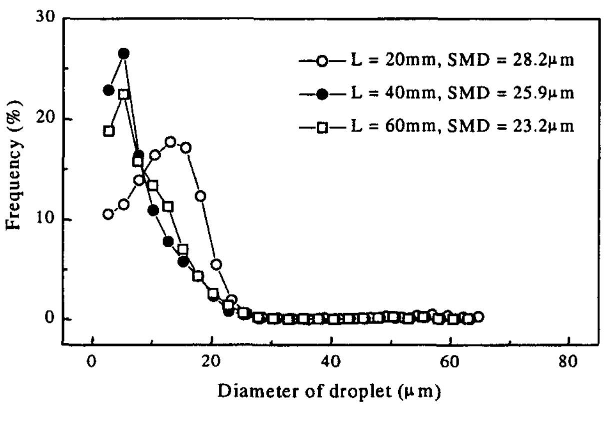

Figure 9. Frequency distribution of diameter of high pressure gasoline injector.

butes to a uniform distribution of fuel droplets at downstream.

Figure 9 indicates the frequency distribution of diameter of high pressure gasoline injector. The droplets size frequency under 25 μm is over 95% at 7 MPa of injection pressure, which means this type of fuel injector delivers a well-atomized spray and degrades unburned hydrocarbon.

3.3. Spatial Velocity Distribution

Figure 10 shows the droplets velocity fields of high pressure gasoline injector including vorticity fields at different moments after injection under 5 MPa of injection pressure and 1msec of injection duration.

The vorticity field is a fundamental characteristics of turbulence and potentially useful in understanding the mixing enhancement between liquid droplets and ambient

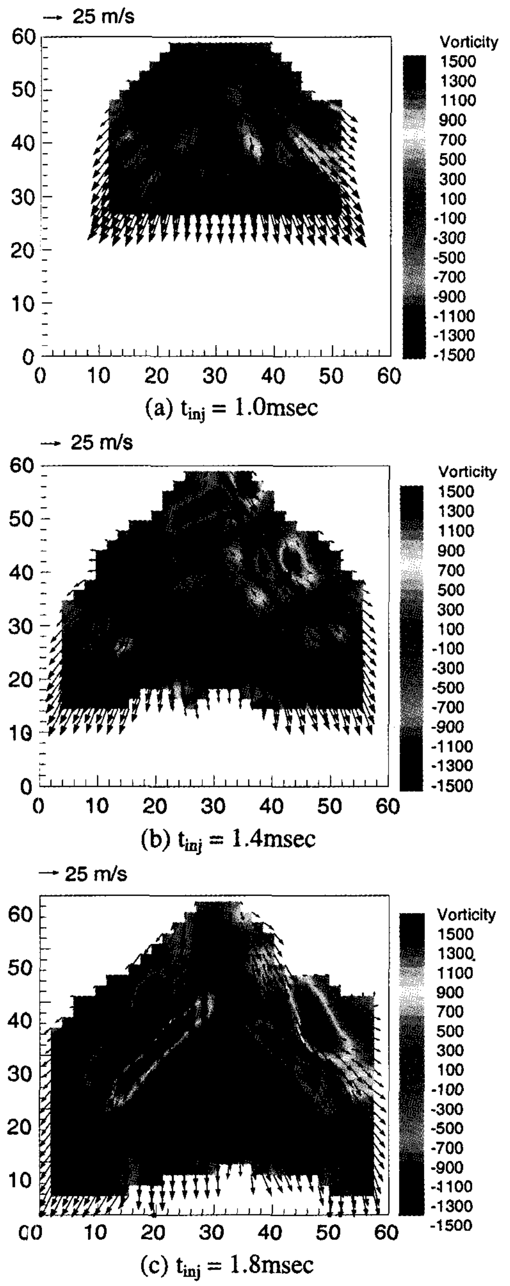

Figure 10. Spray velocity and vorticity fields at different moments after injection (P_{inj} = 5 MPa).

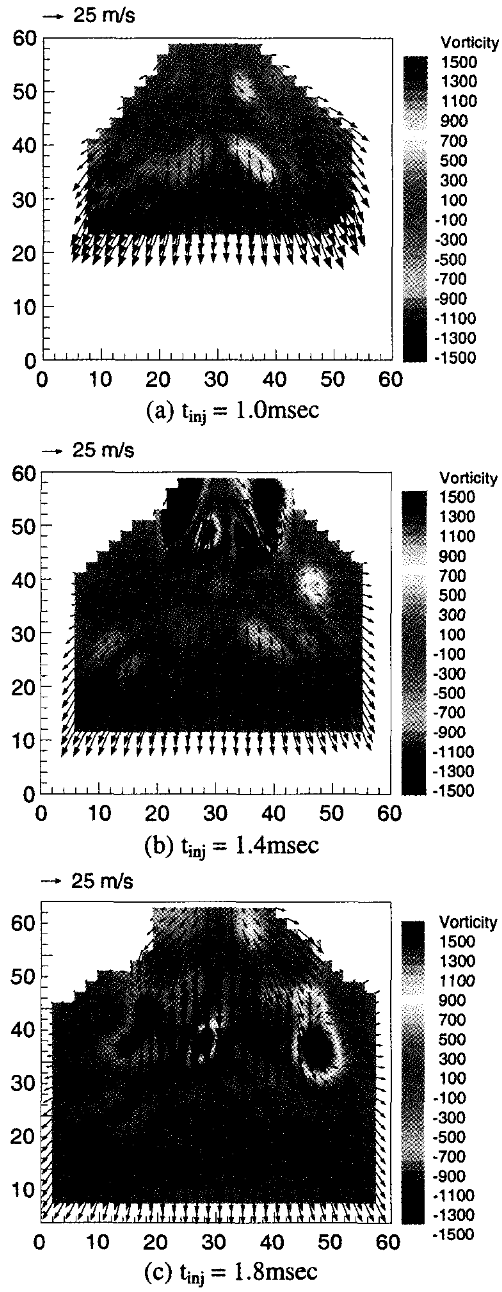

Figure 11. Spray velocity and vorticity fields at different moments after injection (P_{inj} = 7 MPa).

gas. Two-dimensional vorticity field was obtained from velocity field by use of vorticity equation of $1/2(v/x-u/y)$.

Each of these results is averaged from 25 instantaneous velocity fields at every moment after injection At early injection stage of 1.0 msec after injection, the velocity components of liquid droplets are measured to be vertically symmetric and higher velocities are located on the outer edge of spray. These results present the flow characteristics of hollow-cone spray pattern very well and show the good agreement with spray visualization illustrated in Figures 4 and 5. As the time after injection elapses, the velocity field has a tendency to be uniform at downstream because of the effect of upward ring shaped vortex and the faded injection pressure. In addition, it is can be seen that the needle bouncing phenomena becomes visible in this figure.

PIV results at 1.4 msec after injection. In the case of 7MPa of injection, the measured spatial velocity fields and vorticity fields have a similar tendency to the case of 5 MPa of injection pressure as shown in Figure 11.

From the comparison of vorticity as illustrated in Figure 9 and Figure 11, it is observed that the vorticity distributions show the peak value at later stages of elapsed time. In this high vorticity area, it maybe expected the mixing of fuel liquid droplets and ambient gases to be enhanced. But the needle bouncing phenomena come to view more severely at 1.4 msec after injection compared with 5 MPa injection case. This is due to the increase of injection pressure. The needle bouncing phenomena at the end stage of injection causes a harmful effect on liquid droplet evaporation and mixture control. Because it has large sized droplets with high velocity and could be reached at piston surface. Thus, based on these experiment results, it is estimated that the design of nozzle shape should be optimized accordingly to reduce the emission of unburned hydrocarbon.

5. CONCLUSION

An experimental study of the spray structure of the prototype high pressure swirl injector for the application of direct injected gasoline engine has been performed using the laser light scattering method and PDPA technique. The spatial velocity distributions of liquid drops are also measured by PIV system. Based on the information obtained by experimental results, the following conclusions were reached.

(1) From the spray visualization and PDPA experiments, the high pressure swirl injector, which is applied in this study, produces upward ring shape vortex on the spray outer surface caused by interaction between the injection spray velocity and surrounding air. This upward ring shaped vortex promotes the secondary atomization of fuel droplets and contributes to a uniform distribution of fuel droplets.

(2) PDPA measurements indicate that SMD from the tested proto-type injector are measured under 31 mm and droplet size frequency under 25 mm is over 95% at 7 MPa of injection pressure, which means this injector delivers a well-atomized spray and degrades unburned hydrocarbon.

(3) PIV results present the flow characteristics of hollow-cone spray pattern very well and show the good agreement with spray visualization. But the needle bouncing phenomena come to view at the end stage of injection predicted a harmful effect on liquid droplet evaporation and mixture control.

(4) In order to apply high pressure gasoline injector to the direct injected gasoline engine, it is estimated that the design of fuel injector should be optimized accordingly to reduce the emission of unburned hydrocarbon.

ACKNOWLEDGEMENT–This work was supported by Grant No. (2000-2-304-008-3) from the Basic Research Program of the Korea Science and Engineering Foundation.

REFERENCES

Zhao, F., Lai, M-C. and Harrington, D. L. (1997). A review of mixture preparation and combustion control strategies for spark-ignited direct-injection gasoline engines, *SAE Paper No. 970627.*

Yoo, J., Zhao, F., Liu, Y., Lai, M-C. and Lee, K. S. (1997). Characterization of direct-injection sprays under different ambient and fuel injection conditions, *Proc. of ICLASS97*, 498–505.

Iwamoto, Y., Noma, K., Nakayama, O., Yamauchi, T. and Ando, H. (1997). Development of gasoline direct injection engine, *SAE Paper No. 970541.*

Lee, C. S., Lee, K. H., Chon, M. S., Kim, Y. H. and Park, J. S. (1997). The spray characteristics of gasoline injector by using the image processing, *Symposium on Atomization (ILASS-Japan)*, 69–74.

Zhao, F., Lai, M.-C. and Harrington, D. L. (1999). Automotive spark-ignited direct-injection gasoline engine, *Progress in Energy and Combustion Science*, **25**, 446–485.

Lee, C. S., Lee, K. H., Chon, M. S. and Kim, D. S. (2001). Spray structure and characteristics of high pressure gasoline injectors for direct-injection engine applications, *Atomization and Sprays*, **11.1**, 35–48.

Zhao, F., Lai, M.-C. and Harrington, D. L. (1995). The spray characteristics of automotive port fuel injection- A critical review, *SAE Paper No. 950506.*