Effect of injection conditions on the spray characteristics of GDI injectors with different multi-hole configuration

H. J. Kim, S. H. Park, and C. S. Lee*
Department of Mechanical Engineering
Hanyang University
17 Haengdang-dong, Sungdong-gu, Seoul, 133-791, Republic of Korea

Abstract

This study investigates the spray characteristics of multi-hole injectors with two different nozzle hole configurations for a gasoline direct injection (GDI) engine according to the various injection conditions. Two GDI multi-hole injectors with a different location and injection angle of six symmetric holes located around the nozzle axis were used for this investigation on the spray characteristics injected six individual plumes. The spray behaviors such as the spray development process, the spray tip penetration (axial and diagonal direction) from the nozzle tip, and spray cone angle were analyzed from the spray images obtained by using the high speed camera. Also, the local Sauter mean diameter (SMD) according to the axial distance from the nozzle tip and the overall SMD were measured by the droplet measuring system for the comparison between atomization performances of two injectors. It was found that the spray tip penetration and cone angle increase as the injection pressure increases. In the comparison of results between two injectors, test injector with symmetric holes positioned on the periphery of a larger imaginary circle than the other injector, shows small values in the spray tip penetration and cone angle. In the atomization characteristics, the local SMD makes difference according to the axial distance. The effect of injection pressure on atomization of both sprays at the test injectors showed that as the injection pressure increased, local and overall SMD show the decreasing patterns.

Introduction

Since the gasoline engine had been developed, it has been continuously attempted to develop the better fuel consumption, higher power, and environment-friendly engine. Especially, the atmospheric contamination by exhaust gases from automobiles is the first consideration in the environmental issues due to reinforcing restrictions of exhaust emissions. All the countries of the world have strictly restricted the exhaust amount of carbon dioxide (CO2), which caused a global warming, as well as the various exhaust emissions such as hydrocarbon (HC), carbon monoxide (CO), and nitric oxide (NOx). From these reason, the gasoline direct injection (GDI) engine with many advantages lately attracted considerable attention compared to the port fuel injection (PFI) engine.

A GDI engine can be operated in the lean air-fuel ratio as well as the stoichiometric air-fuel ratio and the engine output can be controlled by the fuel amount as a diesel engine. In addition, the GDI engine has no volume loss of intake air because a fuel is directly injected into the cylinder and the charging efficiency of intake air can be increased by a cooling effect of injected fuel evaporation heat. Therefore, a device of GDI engine is somewhat different from that of the conventional PFI engine. The injection pressure in the GDI engine should be more increased than the PFI engine for the short time of injection duration and good mixture between the fuel spray and air in the cylinder. In addition, the combustion chamber shape of flat type is used to improve the engine performance and the design of chamber bowl is optimized for the reduction of exhaust emissions and stratified combustion. In these optimal processes, spray parameters such as an injector location, a spray shape, an injection angle, the number of injector hole, and an arrangement of nozzle hole are the points to be specially considered. In order to form the homogeneous air-fuel mixture, the high pressure multi-hole injector is recently applied to the GDI engine. Investigations on spray and combustion characteristics on the multi-hole GDI injector have been conducted by many researchers. The investigation on the spray developing process from the multi-hole direct injection spark ignition (DISI) engine injector according to the ambient pressure and temperature in the chamber was conducted by Romunde et al.[1]. They reported that the penetration increased by about 20-25% as the ambient pressure decreased from 1.0 bar to 0.5 bar, and the penetration decreased as the ambient temperature decreased due to the increased evaporation rate. The spray formation in the multi-hole nozzles with various ratios of the nozzle hole length to diameter (L/D) was investigated by Skogsberg et al.[2]. They suggested that the Sauter mean diameter reduced as the L/D ratio increased, and the

*Chang Sik Lee, cslee@hanyang.ac.kr

spray cone angle is little affected by variations in either ambient density or temperature. Serras-Pereira et al. [3,4] studied the experimental investigation on the fuel spray development and flame growth of gasoline, ethanol, butanol and iso-octane in the optical DISI engine with multi-hole injector. Dahlander and Lindgren [5] studied the spray formation of four different multi-hole injector with different holes configurations by using various measuring methods experimentally and numerically. Investigations on the spray characteristics of four multi-hole gasoline injectors with different number of nozzle hole under the ambient pressure were performed by Mitroglou et al.[6].They analyzed the spray images and droplet size/velocity, obtained from Mie scattering visualization and phase-Doppler anemometry, according to various operating parameters. This study is to compare and analyze the spray and atomization characteristics of the multi-hole GDI injector of two types with different nozzle holes configuration according to the injection pressure.

Experimental apparatus and Procedure

Figure 1(a) shows the positions of injection hole of high pressure multi-hole GDI injectors with different nozzle hole configurations. Two test injectors have six injection holes and fully symmetric hole arrangement with adjacent angles between two holes of 60 degrees. However, symmetric holes positioned on the periphery of test injector 1 show a larger imaginary circle than those of test injector 2. The schematic of experimental apparatus for the visualization and droplet size measurement of the high pressure multi-hole spray is illustrated in Fig. 1(b). The injector parameters of the energizing duration, peak and hold voltage were controlled by using the injector driver and digital delay/pulse generator (Berkeley Nucleonics Corp., Model 555). The high speed camera (Photron, Fastcam-APX RS) used for the frozen spray images set up a 10,000fps of frame rate with a resolution of 512x512 pixels and a 0.1ms of shutter speed. Two metal-halide lamps were utilized as a light source to obtain a clear spray image. The high speed camera was also synchronized with the injector driver and spray images were stored in a computer with an image grabber by using the digital delay/pulse generator. The phase Doppler particle analyzer (PDPA) was used to measure the microscopic spray characteristics such as the local Sauter mean diameter (SMD), the overall SMD, and droplet distribution. A light source of PDPA is an Ar-ion laser (INNOVA 70C, Coherent) with 0.8 W of laser output and this system consisted of the photomultiplier tube (PMT), transmitter, receiver and signal analyzer. In order to study the spray behaviors according to the angle view, high speed camera is located in an angle of 90 and 180 degrees based on the electrical plug of injector as shown in Fig. 2(a). The spray behavior characteristics of the spray tip penetration (axial/diagonal direction) and spray cone angle according to the angle view were defined from spray images as illustrated in Fig. 2(b). For investigating the atomization performance of two test injectors, the measurement points were selected at 30mm, 50mm, and 75mm from the nozzle tip toward the axial direction. Approximately 15,000 droplets were collected and averaged at three measurement points. Detailed experimental conditions such as the injection pressure, energizing duration, and ambient conditions are illustrated in Table 1.

Results and Discussion

Figure 3 shows the spray development processes of two test injectors at the angle view of 180 degrees according to the time after the start of the energizing. The spray images of two test injectors at the injection pressure of 10MPa were clearer and brighter than those at the injection pressure of 4MPa because the injected fuel mass was increased as the injection pressure increased. The droplets at the outer and end region of injected spray are rolled by the difference of velocity between the injected spray and the ambient air. These phenomena at the injection pressure of 4MPa and 10MPa appeared from the 3.0ms and 4.0ms after the start of the energizing, respectively. The spray development of test injector 1 is a little faster than that of test injector 2 because the initial spray of test injector 1 has narrow angle by the closely hole location compared to the test injector 2. Also, the spray development of test injector 2 shows the strong vortex at the outer and end region of injected spray than that of test injector 1. The spray development processes of two test injectors at the angle view of 90 degrees according to time after the start of the energizing was illustrated in Fig. 4. The spray shapes with an angle of about 20 degrees formed where two lines cross between central line of spray and axis of nozzle tip were appeared in the spray developments of two test injectors due to an eccentric hole arrangement to nozzle center point. In the case of injection pressure of 4MPa, the spray developments of two test injectors shows a similar pattern but the different pattern between the injector 1 and 2 appeared from the 3.0ms after the start of the energizing due to the collapse of spray shape of the test injector 2 at the outer and end region of spray. The spray development processes at the injection pressure of 10MPa show more dense spray image than those of 4MPa. This is why the droplets after the breakup at the end regions of spray moved on both sides at the spray tip by a high injection pressure.

Figure 5 represents the effect of injection pressure on the spray tip penetration of axial and diagonal directions according to the injector at the angle view of 180 degrees. The spray tip penetration of two test injectors at the axial and diagonal direction shows an increasing pattern continuously as the elapsed time after the start of the energizing. The spray tip penetration of test injector 1 at the two measuring direction is larger than the that of test injector 2 because the droplets injected through the injector 1 traveled faster straight than those of injector 2 by the concentrated hole arrangement. In addition, the gap between the injection pressure of 4MPa and 10MPa in the injector 1 has a large value of spray tip penetration compared to that of injector 2. The increasing rate of spray tip penetration of the injector 2 at the injection pressure of 10MPa decreased from the 2.0ms after the start of the energizing because the breakup of droplets actively occurred at the outer and end region of spray by a wide injection angle and reduced droplet momentum. Figure 6 shows the effect of injection pressure on the spray tip penetration of axial and diagonal direction according to the injector at the angle view of 90 degrees. The overall patterns of spray tip penetration show a similar trend as illustrated in Fig. 5. The spray tip penetration of two test injectors at the injection pressure of 4MPa linearly increased however, the increasing rate of spray tip penetration at the injection pressure of 10MPa slowed from the 1.5ms after the start of the energizing. In addition, the increasing rate of injector 2 at the injection pressure of 10MPa is smaller than that of injector 1 because the droplets after the breakup flowed upstream by vortices of spray at the outer spray region of spray. Effect of injection pressure on the spray cone angle of two injectors according to the time after the start of the energizing was shown in Figure 7. The spray cone angle increased as the injection pressure increased. The spray cone angle of test injector 1 rapidly decreased during the early injection stage but it maintained an even value as elapsed time after the start of the energizing. This is because the spray of test injector 1 possesses the characteristics of a forward movement along the initial injection angle. In the case of injector 2, the spray cone angle at the injection pressure of 10MPa continuously increased from the 1.0ms after the start of the energizing due to the strong vortices at the spray tip region.

Figure 8 shows the effect of injection pressure on the local SMD of two test injectors according to the axial distance from the nozzle tip. It can be known that the distribution range of local SMD of two injectors is 20-25μm and it also decreased as the injection pressure increased. On the other hand, the distribution of local SMD according to the axial distance between the test injector 1 and injector 2 is quite different. The local SMD of injector 1 shows an increasing and similar pattern as the axial distance increased. In the case of injector 2, the local SMD has a decreasing trend according as an interval between the measuring point and nozzle tip become more distance. Therefore, it can be said that the injected droplets of injector 1 and injector 2 well atomized around the nozzle tip and at the lower part of spray, respectively. Effect of injection pressure on the overall SMD of two injectors according to the time after the start of the energizing was illustrated in Figure 9. In this study, the overall SMD defined by following equation

$$\text{Overall SMD(t)} = \frac{\left(\sum_{t-\Delta t/2}^{t+\Delta t/2} \sum_{i=1}^{n} D_i^3\right)}{\left(\sum_{t-\Delta t/2}^{t+\Delta t/2} \sum_{i=1}^{n} D_i^2\right)} \quad (1)$$

There is a sharp decrease in the overall SMD of two test injectors until the 0.5ms, and then the overall SMD has the values within the range of 15-25μm from the 0.5ms after the start of the energizing. Also, the overall SMD at the injection pressure of 4MPa is larger than that of 10MPa on the whole, and it is on somewhat increasing trend as elapsed time after the start of the energizing. Figure 10 illustrates the frequency distribution of two test injectors according to the droplet size. The frequency distribution means the proportion of the number of droplets according to the drop diameter to the total number of droplets. Both of two test injectors, the peak of droplets distribution under the drop diameter of 10μm at the injection pressure of 10MPa are higher than that of the 4MPa of injection pressure. This is because the atomization of droplets actively happened by the high injection pressure. In addition, the distribution of injector 2 under the drop diameter of 5μm a little is larger than that of injector 1. Therefore, it can be said that the atomization performance of injector 2 is some better than that of injector 1.

Conclusions

In this work, experimental investigations on the spray characteristics of multi-hole GDI injectors with two different nozzle hole configurations were performed. The conclusions are summarized as follows.

The spray development of test injector 1 is a little faster than that of test injector 2 and the spray development of test injector 2 shows a stronger vortex at the outer and end region of injected spray compared to that of test injector 1. In the spray tip penetration, both test injectors show an increasing pattern continuously as the elapsed time after the start of the energizing. The spray tip penetration of test injector 1 at two measuring direction is larger than that of test injector 2. The spray cone angle of two test injectors increased as the injection pressure increased.

In the atomization characteristics, the distribution range of local SMD of two injectors is 20-25μm and it also decreased as the injection pressure increased. The injected droplets of injector 1 around the nozzle tip and injector 2 at the lower part of spray are atomized, respectively. There is a sharp decrease in the overall SMD of two test injectors until the 0.5ms, and then the overall SMD has the values within the range of 15-25μm. Also, the peak of droplets distribution under the 10μm at the 10MPa is higher than the 4MPa of injection pressure. The distribution of injector 2 under the drop diameter of 5μm a little is larger than that of injector 1. Therefore, the atomization performance of injector 2 is some better than that of injector 1.

Acknowlegdment

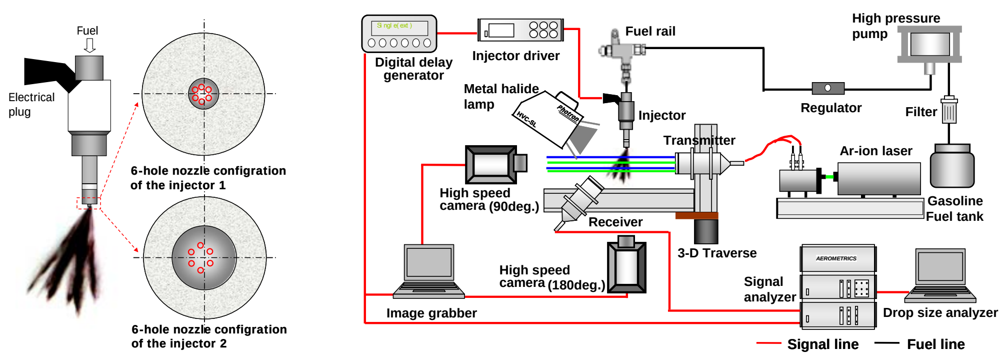
This study was supported by the Center for Environmentally Friendly Vehicles (CEFV) of the Eco-STAR project from the Ministry of Environment (MOE), Republic of Korea. Also, this work was supported by the Second Brain Korea 21 Project in 2008.

References

1. Romunde, Z., Aleiferis, P.G, Cracknell, R.F., Walmsley, H.L., *SAE Technical paper series* 2007-01-4032 (2007)
2. Skogsberg, M., Dahlander, P., Lindgren, R., Denbratt, I., *SAE Technical paper series* 2005-01-0097 (2005)
3. Serras-Pereira, J., Aleiferis, P.G, Richardson, D., Wallace, S., *SAE Technical paper series* 2007-01-4033 (2007)
4. Serras-Pereira, J., Aleiferis, P.G, Richardson, D., Wallace, S., *SAE Technical paper series* 2008-01-1591 (2008)
5. Dahlander, P., and Lindgren, R., *SAE Technical paper series* 2008-01-0136 (2008)
6. Mitroglou, N., Nouri, J.M., Yan, Y., Gavaises, M., Arcoumanis, C., *SAE Technical paper series* 2007-01-1417 (2007)

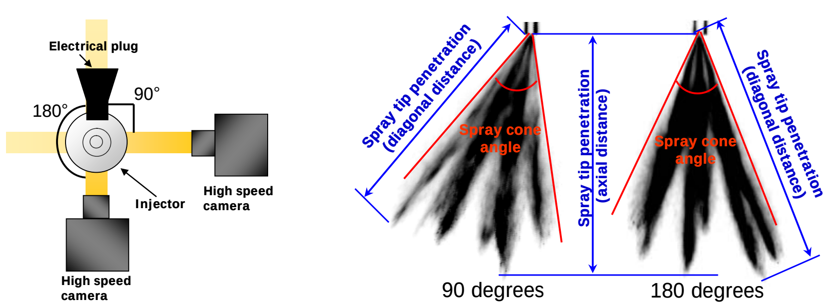
Table 1. Experimental conditions

Items	Parameters
Injection pressure	4MPa, 10MPa
Energizing duration	2.0ms
Ambient condition	Atmospheric condition (0.1MPa, 293K)
Measuring points of droplets	3 points (30/50/75mm from the nozzle tip)



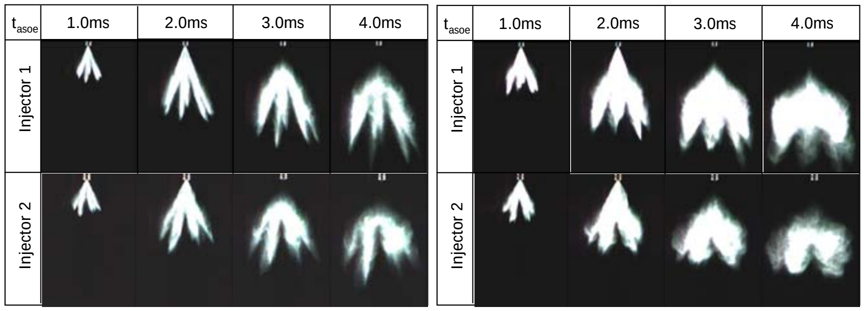
(a) Nozzle configurations of test injectors (b) Experimental apparatus

Figure 1. Nozzle configurations of two multi-hole GDI injectors and experimental apparatus



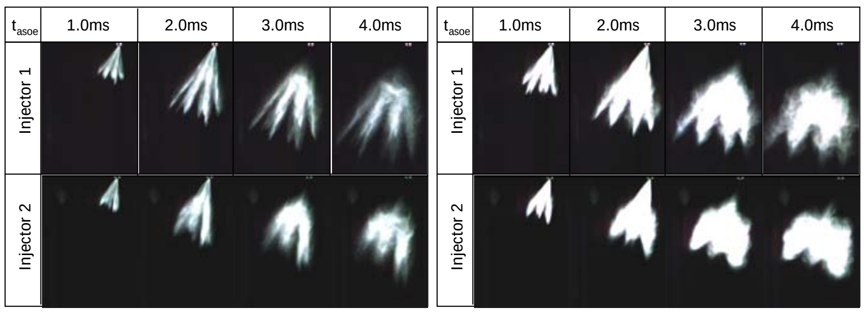
(a) Measurement location (b) Definitions of spray characteristics

Figure 2. Measurement location and definitions of spray characteristics for the visualization of spray shape



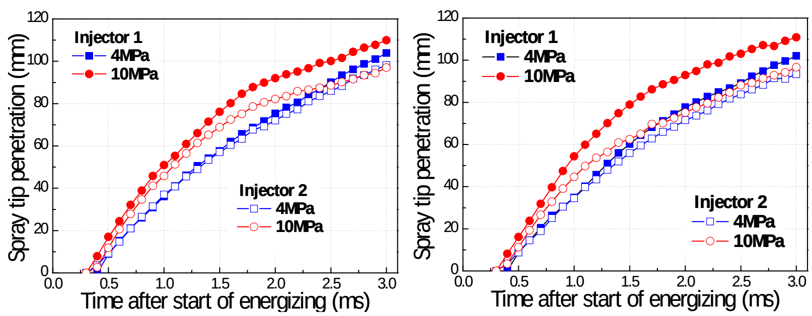
(a) P_{inj} = 4MPa (b) P_{inj} = 10MPa

Figure 3. Spray development processes of two injectors (view angle : 180 degrees)



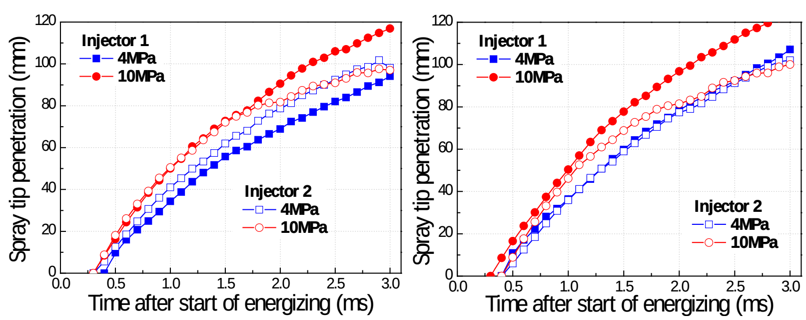
(a) P_{inj} = 4MPa (b) P_{inj} = 10MPa

Figure 4. Spray development processes of two injectors (view angle : 90 degrees)



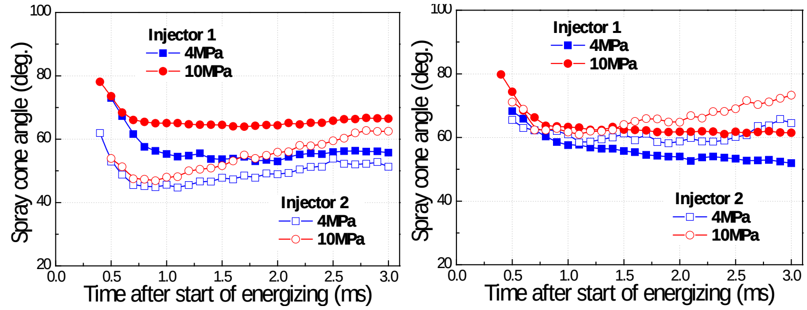
(a) Axial direction (b) Diagonal direction

Figure 5. Effect of injection pressure on the spray tip penetration of axial and diagonal direction according to the injector (view angle : 180 degrees)



(a) Axial direction (b) Diagonal direction

Figure 6. Effect of injection pressure on the spray tip penetration of axial and diagonal direction according to the injector (view angle : 90 degrees)



(a) view angle (90 degrees) (b) view angle (180 degrees)

Figure 7. Effect of injection pressure on the spray cone angle of two injectors according to the time after the start of the injection

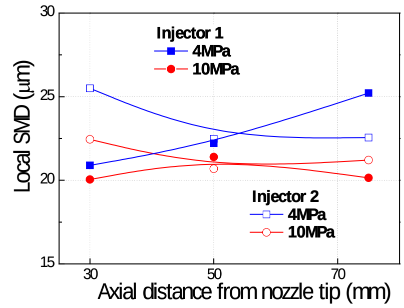
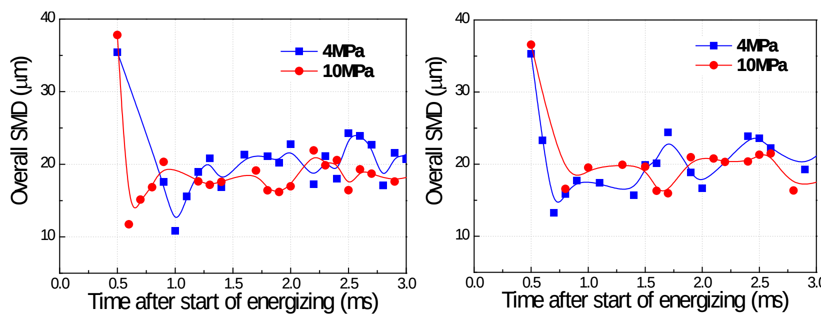
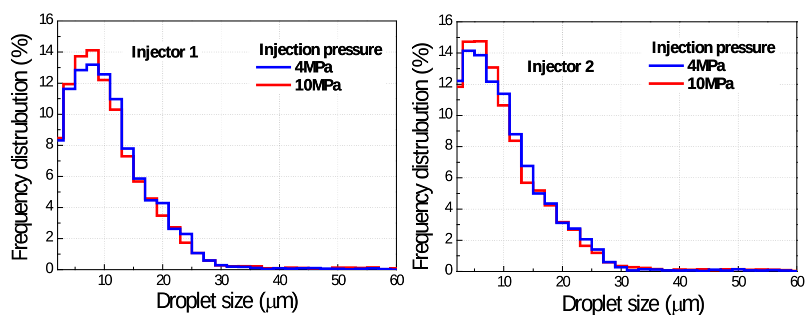


Figure 8. Effect of injection pressure on the local SMD of two injectors according to the axial distance from the nozzle tip



(a) Injector 1 (b) Injector 2

Figure 9. Effect of injection pressure on the overall SMD of two injectors according to the time after the start of the injection



(a) Injector 1 (b) Injector 2

Figure 10. Frequency distribution of two injectors according to the droplet size