Fuel-Spray Characteristics of High Pressure Gasoline Injection in Flowing Fields*

Jaejoon CHOI**, Seokhwan LEE**, Hyundong SHIN** and Choongsik BAE**

The direct injection into the cylinder has been regarded as a way of the reduction in fuel consumption and pollutant emissions. The spray produced from the direct injector is of paramount importance in GDI (Gasoline Direct Injection) engines in that the primary atomization process must meet the requirement of quick and complete evaporation and combustion especially to prohibit the excessive HC emissions. The spray geometry must be stable and compact showing controlled mixture formation by taking a benefit from in-cylinder charge flows.

The interaction between air flow and fuel spray was investigated in a steady flow system embodied in a wind tunnel to simulate the variety of flow inside the cylinder of the GDI engine. The spray developments in flowing fields with the mean velocity up to 17m/s were at first identified by spray visualization. The direct Mie scattered images and Shadowgraph images presented the macroscopic view of the liquid sprays and the spatial distribution of vapor fields. The microscopic characteristics of the spray were investigated by the velocity and particle size measurements using a Phase Doppler Anemometer (PDA). The processes of atomization and evaporation with a GDI injector were observed and consequently utilized to construct the data-base for the spray and fuel-air mixing mechanism as a function of the flow characteristics. This could give the way of optimization between the flow formulation and injection schemes in GDI engines.

Key Words: GDI Injector, Crossflow, Late Injection

1. Introduction

Gasoline direct injection (GDI) or direct-injection spark-ignition (DISI) engine became an important initiative of future SI engines due to its potential for significantly enhanced fuel economy and transient response. The process of fuel injection, spray atomization, vaporization and mixture preparation coupled with in-cylinder air motion are all being researched for the optimization of this promising combustion system(1). Because there are rapid changes in pressure and temperature inside the engine when the fuel injected into the cylinder, many researchers have sought the ways to understand the in-cylinder motion by investigating the fuel spray characteristics in the constant-volume chamber at the elevated pressure and temperature(2). However, the flows in the cylinder have not been modeled many times(3). When the GDI engine runs under lean burn operation, the fuel is injected late in compression stroke(4),(5). When the late injection starts, though the velocity inside the cylinder varies seriously, the in-cylinder maximum average velocity is about 15m/s(6), so that the interaction between in-cylinder motion and injected spray is very important.

This paper aims to accumulate fundamental data of spray and flow interaction through the investigation on the fuel spray in the fast crossflow of a wind tunnel. Sheet beam Mie scattering image technique and shadowgraph image technique were used to overview the macroscopic spray pattern of both liquid and vapor gasoline, while PDA (Phase Doppler Anemometry) system was used to measure the microscopic characteristics; size and velocity of the liquid fuel droplets.

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2. Experimental Apparatus

The wind tunnel was used to produce flowing environment as shown in Fig. 1 incorporated with measurement tools. The maximum speed of air flow was 17m/s. The velocity of the flow can be controlled by adjusting the speed of the blower. The uniformity of the flow at the various speed was tested by pitot tube. When the flow rate has its maximum value, the deviation between the maximum and minimum speed of the wind in the test section was around 5%. Optical access was allowed through transparent acryl window at the test section of 200mm´200mm. To study the interaction between the flow and the fuel spray macroscopically, Mie scattering image technique using laser sheet beam was applied. 0.75W water-cooled Ar-ion laser was used for the light source. The laser light transmits a cylindrical lens with focal length 6.5mm to make sheet beam. It is incident on the test section for the optical access of injection spray. ICCD camera(Stanford Quick05A) was used for capturing the Mie scattering image with exposure time of 10ms.

Shadowgraph image technique was used to visualize both liquid and vapor fuel spray development. Ar-ion laser was used for the light source, and parallel beam bundle was made between two concave mirrors with diameter 200mm and focal length 2m so that the shadow image was projected to the ICCD camera. PDA(Phase Doppler Anemometry) system was used to measure liquid fuel particle diameter and velocity. The specification of the PDA system is denoted at Table 1. At this experiment, the characteristics of the vortices were investigated at 7cm away from the injector tip to axial direction so that the velocity field was obtained by scanning along the crossflow direction. The fuel vaporization effects by the different crossflow velocity were investigated by obtaining the temporal variation and spatial average of SMD value.

Fig. 2. The spray shape at different injection pressures (Mie scattering image, crossflow velocity 0m/s, 2.5ms after SOI) (a) 3MPa (b) 5MPa (c) 7MPa

Fig. 3. Definitions of spray geometry : 1. main spray penetration  2. solid jet penetration  3. spray width

Table 1. Specification of PDA system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Laser Wavelength</td>
<td>514.5nm</td>
</tr>
<tr>
<td>Transmitter Focal Length</td>
<td>250mm</td>
</tr>
<tr>
<td>Beam spacing at transmitter</td>
<td>40mm</td>
</tr>
<tr>
<td>Receiving Lens Focal Length</td>
<td>300mm</td>
</tr>
<tr>
<td>Measurement length</td>
<td>1.4mm</td>
</tr>
<tr>
<td>Measurement diameter</td>
<td>0.114mm</td>
</tr>
</tbody>
</table>
GDI swirl injector whose early spray angle is 60° was used, and it was set up perpendicularly to the crossflow. The nozzle tip is located 8mm below the top wall along the centerline of the cross section. Injection pressure was varied to 3MPa, 5MPa, 7MPa when the cross flow velocities were 0m/s, 5m/s, 10m/s, 15m/s. The spray characteristics of the 5 mili-second injection duration were investigated as a function of injection pressure and crossflow velocity. The relation between the injection pressure and the weight of the gasoline fuel at one injection is shown at Table 2.

Table 2 Relation between weight of fuel and injection pressure

<table>
<thead>
<tr>
<th>Injection pressure</th>
<th>Weight of fuel per injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 MPa</td>
<td>32.44mg</td>
</tr>
<tr>
<td>5 MPa</td>
<td>41.35mg</td>
</tr>
<tr>
<td>7 MPa</td>
<td>47.87mg</td>
</tr>
</tbody>
</table>

3. Results

The Mie scattering pictures from various injection pressures were obtained and shown in fig. 2. The central solid jet which was due to the sac volume inside the injector, which was inwardly opening type, was detected in the middle and lower bound in every picture. The solid jet would induce the wetting to the cylinder and piston bowl, affecting UHC(Unburned Hydrocarbon) emission. As the injector pressure increased, the intensity of Mie scattering image was increased. Spray penetration depth and width were measured from the Mie scattering image.

Figure 3 shows the description of the spray geometry. The solid jet penetration means the length between the injector tip and spray tip induced by the sac volume, while the main spray penetration means the distance between the injector tip and the end of the main swirl spray. Fig. 4 shows the characteristic lengths of the spray with the various injection pressures and crossflow velocities. The penetration depth of solid jet(tip) to the time has a tendency to increase as injection pressure increases. But the main spray penetration depth proved to be almost the same values though the injection pressure was varied by three values. The spray width and main spray penetration depth were measured at the injection pressure 5MPa as shown in Fig 4(b). From the Mie scattering images at Fig. 2, the scattering intensity became faint that the vaporization process became faster as the crossflow velocity was high. The spray
Width has almost the same values regardless of the crossflow velocity, and so the main spray penetration is. Moreover, when the crossflow velocity becomes faster, the spray width from the Mie scattering images is observed to decay due to the rapid vaporization process at 3.5 ms after SOI.

Figures 5 and 6 show the Mie scattering images.

Fig 6. Spray developments at crossflow velocity 15 m/s (Mie scattering image, injector pressure 5 MPa) 
(a) 1 ms (b) 3 ms (c) 5 ms (d) 7 ms after SOI

Fig 7. Spray development at crossflow velocity 0 m/s (Shadowgraph image, injector pressure 5 MPa)
(a) 1 ms (b) 3 ms (c) 5 ms (d) 7 ms after SOI

Fig 8. Spray development at crossflow velocity 15 m/s (Shadowgraph image, injector pressure 5 MPa)
(a) 1 ms (b) 3 ms (c) 5 ms (d) 7 ms after SOI

Fig 10. The pure vapor images (overlapping of Mie scattering and Shadowgraph images)
when the crossflow velocity was 0m/s and 15m/s when the injector pressure was 5MPa. The development of the rotating vortex at the spray skirt is detected in the initial spray at 1ms, at the crossflow velocity 15m/s, although there seems to be no vortex at 3ms, 5ms after SOI (Start Of Injection) but, at 7ms, the vortex is proved to be continuously maintained in the structure, and the vortex motion dominates the whole spray pattern moreover. At Fig. 6(d), the two vortices make the shape of character ‘8’ which was not seen in the quiescent case of crossflow velocity 0m/s. The vortex entrains the air to the fuel spray cloud and has a role of mixing the air and fuel. On the other hand, when the crossflow velocity is 0m/s, the vortex development process can be detected in whole time series. The intensity of the Mie scattering image is decreased with time to show the proceeding of the fast vaporization and atomization.

The Shadowgraph images at the crossflow velocity 0m/s and 15m/s are shown at Figs. 7 and 8, respectively. Although the vortex motion is not distinguishable as in the Mie scattering images, the vaporized fuel which is distinct from the air in the density was detected simultaneously with the liquid fuel. The evaporation of fuel at the tip of circumferential vortex was observed at 3ms after SOI. In the Mie scattering image at 7ms after SOI, the intensity of the image was very weak while the clear image of the movement of the vaporized fuel with vortex motion was detected in the shadowgraph image. It is easy to observe the vortex formation at the early time in the fuel spray at faster crossflow. The faster the crossflow velocity becomes, the more does the vaporization process proceed rapidly. It is proved by the fact that more vaporized fuel at the faster crossflow is qualitatively observed than that at quiescent surroundings. The vaporized fuel was also found to rapidly follow the crossflow because the density of the vaporized fuel is far lower than that of liquid fuel.

Fig 9 shows the shadowgraph images of the various crossflow velocity of 0m/s, 5m/s, 10m/s,
15m/s with injection pressure 5MPa at 4ms after SOI. As the crossflow velocity gets higher, the liquid fuel and vaporized fuel are simultaneously chasing the crossflow, and the vaporized fuel is detected easily. The formation of the vortex motion was more easily observed at the lower level of the crossflow velocity. When the crossflow velocity is high, it is not detected which seems to follow the crossflow. But the existence of the vortex has very important role in the vaporization process and the mixing of the fuel and air as the Mie scattering images, show in Fig. 6.

Figure 10 shows the combined pictures between shadowgraph and Mie scattering images. The liquid fuel at Mie scattering image was processed to the white color and was overlapped to the shadowgraph image to show only the behavior of fuel vapor. Rapid vaporization process proceeds with time. The faster the crossflow velocity gets, the less amount of liquid fuel was observed from the Mie scattering image in the figure.

Figure 11 shows the axial velocity profile at axial distance 7cm from injector tip along crossflow direction. The velocity profile indicates vortex structure moving through the measurement line. Particularly, when the crossflow velocity is 15m/s, two vortices can be shown moving downstream without its structure destructed as was confirmed in Mie scattered image. Fig 11(c) shows the existence of two vortices with different strength. The existence of these vortices leads the air entrainment and air-fuel mixing even in strong flow field as in the GDI engines with high pressure swirl injectors.

Figure 13 shows the fuel particle diameter and SMD with time averaged in spray field at crossflow velocity 0m/s and 10m/s. The points describe raw data by PDA measurement showing the distribution of fuel particle diameter itself, and the lines show their spatial averaged SMD (Sauter Mean Diameter). The PDA measuring points are shown in Fig. 12. Though the raw data are dispersed a lot, the lines of SMD shows when the 10m/s crossflow exists, the distribution of SMD is smaller than when the crossflow does not exist due to the vaporization of small fuel particles. Simple interpretation of SMD shows that the spray in crossflow field is better atomized leading higher possibility of vaporization. More detailed measurements, scheduled in the series of this work, would provide size distribution in whole spray field which can clearly show the effect of flow on the atomization and evaporation.

4. Conclusion

High pressure swirl injection characteristics of a GDI injector in the crossflow up to 15m/s were investigated to study the interaction between flow and spray. The velocity 15m/s was selected to simulate the averaged mean velocity in the cylinder when the fuel is injected late in the cylinder for the engine to make stratified combustion.

1. The solid jet penetration depth varied with injection pressure, but the main spray penetration depth and the spray width were not affected by the injection pressure and the crossflow velocity.
2. Fuel vaporization rate was found to be proportional to crossflow velocity.
3. Liquid and vapor fuel were distinguished by Mie scattering images and shadowgraphy. When the crossflow velocity is fast, the fast movement of fuel can be detected toward the downstream of crossflow induced by the momentum of crossflow as well as toward axial direction by the injection pressure.
4. The velocity data showed the existence of vortices and the velocity profile showed the vortex motion at various crossflow velocity.
These vortices made in high pressure swirl injection would lead air entrainment and consequently air-fuel mixing even in strong flow field.

5. The measured SMD data by PDA measurement showed the vaporization process showing the interaction between fuel and flow. The more intense atomization and evaporation is expected in stronger flow field.

Acknowledgement

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