PDA MEASUREMENT OF TRANSIENT SPRAY FORMED BY A DISI MULTI-HOLE INJECTOR

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ABSTRACT The droplet characteristics of unsteady fuel spray formed by multi-hole injector used in direct injection gasoline engine was investigated. In order to understand the detail structure of transient spray, a phase Doppler anemometer was used. The traverse system of the vessel was designed to obtain two-dimensional structure of spray. The laser power at measurement volume was optimized in order to detect relative smaller droplets. It is necessary to evaluate the effect of laser power of measurement volume on detection limit of smaller droplets under 10 μm. Phase locking method was used to analyze ensemble mean value of axial/radial droplet velocity, axial/radial slip velocity, relative droplet Reynolds number, and droplet turbulent kinetic energy. As a result, smaller droplets under 10 μm can follow the entrainment vortex at the spray shell. On the other hand, larger droplets over 30 μm have larger velocity to penetrate the entrainment vortex. Intermediate droplets of 15<D≤20μm in diameter are criteria for follow/penetration of vortex.

Keywords: Multi-hole Injector, Entrainment Structure, Size-Classified Droplet Behavior, Turbulent Kinetic Energy

1. INTRODUCTION

Direct injection spark ignition (DISI) engine has great potential to achieve higher thermal efficiency and lower exhaust emissions [1-4]. Fuel injection systems for DISI engine provide both late injection for stratified charge combustion at part load, as well as early injection during the intake stroke for homogeneous-charge combustion at full load. Currently most DISI engines use a wall-guided direct injection system. This system has several problems including excessive unburned hydrocarbon emissions, high soot production due to the fuel attachment on the piston bowl. Next generation of DISI engines utilizes a spray-guided direct injection system. The spray guided system generates a stratified fuel concentration near a spark plug due to the direct fuel injection toward a spark plug. Multi-hole injector has a potential to use in a spray guided system in order to multiple spray plume and strength to the air flow, and back pressure inside the cylinder.

Several researches have applied the multi-hole injector to the DISI engines as a spray guided concept [5-10]. Ortmann et al. reported the combustion and emission characteristics of swirl injector and multi-hole injectors used in wall-guided and spray-guided combustion systems [5]. Spray-guided combustion system with swirl injector is very sensitive to the spray characteristics, while multi-hole injector system can indicate the improvement of fuel consumption and emissions. Smith et al. investigated ignition stability in an optical spray-guided DISI engine with a multi-hole injector using high-speed PLIF system [10]. Skogsberg et al. measured mixture formation process of 6 hole injector using LIEF, PDA and numerical calculation [6]. Key features of designing of multi-hole injector are the spray plume formation process from one injection hole and collapse of spray plume. Therefore detailed spray characteristics from one injection hole should be investigated.

The purpose of this study is to investigate the unsteady spray structure formed by one hole of multi-hole injector using a phase Doppler anemometer. Optimization of PDA system was done in advance in order to obtain smaller droplets. Phase locking method was used to analyze ensemble mean value of axial/radial droplet velocity, axial/radial slip velocity, relative droplet Reynolds number, and droplet turbulent kinetic energy.

2. EXPERIMENTAL SET-UP

2.1 Multi-hole Injector and experimental set-up

The gasoline engine multi-hole injector used in this study is prototype that was fabricated specifically for research use [8, 9]. Usually this kind of injector has multi-hole, such as 6 or 8 holes. In this research, in order to focus on the primary spray structure of one spray plume, therefore, 2 holes injector is produced. This 2 holes injector has a spray angle at 90 degree. Safety gasoline (Dry-solvent, density: 770 kg/m3, surface tension: 2.45x10-2 N/m) is used as a fuel instead of gasoline. The injector has an inwardly opening needle. The diameter of nozzle exit is φ0.21 mm.

Figure 1 shows schematically the experimental set-up for investigation of the primary spray structure of high-pressure multi-hole injector. The closed vessel used was a steel cylinder, 150 mm in diameter and about 350 mm long. The multi-hole injector is mounted on the upper end plate of the closed vessel. The closed vessel has four quartz windows for the optical access. The ambient (back) pressure inside the vessel can be changed by an air-compressor. The multi-hole injector is controlled with an electric injector driver, requiring a high voltage power source and external trigger input for injector pulse width control. Nitrogen gas was used to pressurize the fuel supply
system and provides adjustable fuel delivery pressure up to 10MPa.

In this study, the droplet characteristics of unsteady fuel spray formed by multi-hole injector used in direct injection gasoline engine was investigated. The experiments were performed with an injector pressure of 7 MPa in a closed vessel under atmospheric condition.

The transient whole spray was shown in Fig. 2 [11]. Delay time denotes the elapsed time from the injection start signal. The development of one of the spray plume can be seen. Three stages in the development of spray can be identified: (1) the initial stage (Delay=0~0.8 ms); (2) the quasi-steady state (Delay=0.8~1.8 ms); (3) the post-injection stage.

Figure 3 indicates the effects of injection pressure on the whole spray images and primary spray near nozzle exit [11]. The injection pressure was changed at 3, 5, 7 and 10 MPa. Injection duration under each injection pressure condition was determined to obtain the same total mass of fuel. It can be seen that volume of one spray plume increases at higher injection pressure. Higher injection pressure causes larger mass of spray plume during exposure time.

2.2 Optimization of PDA system

For fuel droplet diameter and velocity measurements, a phase Doppler anemometer (60X41, 62N55: Dantec Dynamics) was used. An optical-fiber-linked phase Doppler anemometer was mounted on a horizontal bench as shown in Fig. 1. An argon-ion laser was used and the laser power on measurement volume was optimized, shown in later. The scattering angle of 68 degree was determined by first order

<table>
<thead>
<tr>
<th>Delay, ms</th>
<th>0.324</th>
<th>0.708</th>
<th>1.092</th>
<th>1.476</th>
<th>1.860</th>
<th>2.244</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering image</td>
<td>Speed:32kfps Exposure:8μs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20mm</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 2 Time-series of whole spray image

<table>
<thead>
<tr>
<th>Pinj, MPa</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering image</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backlight image</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5mm</td>
<td></td>
<td></td>
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</tbody>
</table>

Fig. 3 Effect of injection pressure on spray image
refraction angle. Closed vessel with injector is set on the transverse system in order to obtain the whole feature of injection spray. This system can transverse the closed vessel with 100 μm in spatial resolution. The focal length of the transmitting optics was 400 mm, while the receiving optics had a 310 mm focal length. 25,000 samples were detected at each measurement point.

When the PDA system is applied to the fuel injection spray, it is necessary to measure the relative smaller droplet under 10 μm in diameter accurately. Effects of laser power at the measurement location on detection of smaller droplets should be considered in PDA measurement. The effects of laser power on detection of smaller droplets were investigated by changing the laser power from transmitting optics shown in Table 1. Figure 4 indicates the droplet diameter and axial velocity distributions at 50 mm below the nozzle along center axis under 7 MPa of injection pressure.

There is little difference in axial droplet velocity distribution, on the other hand it is difficult to detect smaller droplets under 10 μm under condition 1 and 2 due to the lack of laser power to obtain enough scattering light. Smaller droplet under 10 μm can be detected under condition 3 of laser power higher than 50 mW in each transmitting beam. It is necessary to check the laser power on detection of smaller droplets in gasoline injector.

Next, it is necessary to analyze droplet behavior in time-series from start of injection for unsteady gasoline injection. In this research, obtained PDA results include signal of start of injection. Phase-locking method was used to analyze the time-series of droplet behavior from start of injection signal. Time bin width for analyzing ensemble averaged droplet behavior should be considered because PDA data is a discrete data series for detecting the traveling droplet inside measurement volume. Figure 5 indicates the typical raw data of axial droplet velocity at (0, 10), and (2, 25). At (0, 10) near the nozzle exit, axial droplet velocity indicates over 110 m/s during 2.5ms from the start of injection signal. These droplet velocities have large velocity range. At (2, 25), axial droplet velocity shows lower than (0, 10) point. This figure indicates the advantage of phase locking method to analyze the ensemble data for unsteady gasoline injector.

Here, bin width for analyzing the Sauter mean diameter and ensemble averaged droplet velocity should be considered. Longer bin width can indicates higher sample number, but it is difficult to detect the difference of time-series of droplet behavior. Shorter bin width has problem to detect averaged data due to the lack of sample number. Therefore, optimization of bin width should be carried out. Figure 6 indicates the ensemble averaged axial droplet velocity and sample number for 0.050, 0.100, 0.250, 1.000 ms as bin width. At the spray tip, there is strong momentum decay. At the bin width of 0.050, 0.100, 0.200 ms, the spray tip motion and steep velocity can be observed, while the velocity could not be shown in 1.000 ms of bin width. However, detected sample number of 0.050 ms as bin width is very small so that it is difficult to analyze size-classified droplet behavior, shown in experimental results. In this research, 0.100 ms as bin width is selected due to enough obtained sample number. Figure 7 indicates the ensemble averaged axial droplet velocity for 0.100 ms as bin width at (0, 10), and (2, 25) points. Averaged spray tip velocity indicates almost 90 m/s at near the nozzle exit. On the other hand, spray tip velocity at (2, 25) has two peaks at 0.5ms and 2.0 ms after the start of injection signal. Ensemble analysis can indicate the detail droplet behavior of spray tip, while it is difficult to detect the velocity fluctuation using raw data. This bin width should be determined in consideration of obtained sample number.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Radial(488nm)</th>
<th>Axial(514.5nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28mW</td>
<td>26mW</td>
</tr>
<tr>
<td>2</td>
<td>38mW</td>
<td>59mW</td>
</tr>
<tr>
<td>3</td>
<td>50mW</td>
<td>68mW</td>
</tr>
</tbody>
</table>

Table 1 Laser power

Fig. 4 Effect of laser power on measured droplet size

Fig. 5 Raw data of axial droplet velocity
3. EXPERIMENTAL RESULTS

In this research, droplet dynamics such as followability, penetration characteristics and droplet dispersion at high shear region and spray tip is considered. The Phase Doppler technique can measure the droplet diameter and its velocity (axial and radical) at local point. Size-classified technique was applied to analyze the droplet characteristics [12-14].

Figure 8 shows size-classified axial droplet velocity using the raw data of Fig. 5. Droplet dynamics was classified into 6 groups, such as under 5 μm, 5<D<10μm, 10<D<15μm, 15<D<20μm, 20<D<30μm, over 30μm. At (0, 10) near the nozzle exit, larger droplets over 15 μm indicated over 90 m/s during 2.5 ms from start of injection signal, while smaller droplets under 10 μm show the velocity of about 70 m/s. Larger droplets have larger momentum and indicate the strong penetration.

In order to have whole image of transient injected spray, size-classified velocity was demonstrated in Fig. 9. Figure 9 includes direct image obtained with a high-speed video camera. At t=1ms from start of injection signal, smaller droplets under 10 μm indicates larger velocity downstream along the center axis and entrainment vortex at the spray shell. This vortex moves toward downstream after 2ms. The momentum decay is shown in 4ms after start of injection signal. The entrainment vortex was caused at the spray shell and consisted of smaller droplets less than 10 μm. On the other hand, larger droplets over 30 μm show larger spray angle and strong penetration at entrainment vortex shown in smaller droplets at 3ms after start of injection signal. These droplets indicate larger droplet velocity until 3ms. Intermediate droplets of 15<D<20μm in diameter is criteria for followability.

Figure 10 indicates how injected droplets distribute in transient spray from injection nozzle. Size-classified sample number is shown in Fig. 10. Droplets of 5<D<10μm have large number of sample number, and distribute in whole spray at 4ms after start of injection. Larger droplets over 30 μm have strong penetration and move toward down stream with higher velocity at 4ms.

For further understanding of spray tip development, aerodynamics of droplet behavior is investigated using slip velocity between air flow motion and droplet behavior. In this research, smaller droplets under 5 μm in diameter was used as air flow motion due to the followability. Size-classified slip velocity can be estimated between motion of smaller droplets less than 5 μm and size-classified droplet velocity. Relative droplet Reynolds number can be estimated using slip velocity, expressed in Eq. (1).

\[
\text{Re}_\rho = \rho_a \sqrt{V_p - V_a} D_p / \mu_a
\]

![Fig. 6 Effect of bin width on PDA results](image)

![Fig. 7 Ensemble average data](image)

![Fig. 8 Size-classified axial droplet velocity](image)
where, \( \rho_a \) and \( \mu_a \) are the density and the viscosity of air respectively, \( V_a \) is the airflow velocity vector and \( D_p \) and \( V_p \) are the average droplet diameter and velocity vector for each size class. The overbar indicates that these quantities are taken as averages over bin width.

Figure 11 shows size-classified slip velocity in axial direction. Smaller droplets under 15 \( \mu \)m indicate smaller slip velocity at (0, 10), and (2, 10) near the nozzle. Droplets of \( 15 < D \leq 20 \mu \)m indicates larger slip velocity at spray tip. Slip velocity at (0, 30) and (2, 30) apart from the nozzle exit, indicates the smaller value due to the momentum decay. Larger droplets over 30 \( \mu \)m in diameter have larger slip velocity due to the strong penetration at the spray tip.

Figure 12 indicates the relative droplet Reynolds number. Smaller droplets under 15 \( \mu \)m have relative smaller value showing followability to air flow, while larger droplets over 20 \( \mu \)m will have drag due to momentum decay. Droplets of \( 15 < D \leq 20 \mu \)m in diameter is criteria for follow/penetration at spray tip.

Finally, the turbulent kinetic energy of droplet as defined by Eq. (2) is shown in Fig. 13.
\[ k = \frac{(u^2 + v^2)}{2} \]  

where, \( u \): axial velocity, \( v \): radial velocity.

At \((0, 19)\), smaller droplets have large fluctuation of velocity, while larger droplets have large turbulent kinetic energy at \((2, 10)\) due to the large fluctuation at spray shell. Larger droplets have the drag due to the momentum decay at spray shell. At downstream \((0, 30)\), and \((2, 30)\), all droplets indicate almost same value due to the momentum decay.

Using size-classified droplet data, aerodynamics feature and turbulent kinetic energy can be discussed for better understanding of droplet characteristics of unsteady gasoline injection.

4. CONCLUSIONS

The droplet characteristics of unsteady fuel spray formed by multi-hole injector used in direct injection gasoline engine was investigated. The results obtained in this research are summarized as follows:

1. It is necessary to evaluate the effect of laser power of measurement volume on detection limit of smaller droplets under 10 μm. Phase locking method is effective to analyze the droplet characteristics of unsteady injected spray.

2. Smaller droplets under 15 μm can follow the entrainment vortex at the spray shell. On the other hand, larger droplets over 20 μm have larger velocity to penetrate the entrainment vortex. Intermediate droplets of 15<\(D\leq20\)μm in diameter is criteria for follow/penetration of vortex.

REFERENCES


