Effects of injector valve movement on diesel spray characteristics under short full valve opening

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Abstract
A laser 2-focus velocimeter (L2F) was used for the measurement of diesel fuel sprays. Temporal and spatial changes in the number, velocity and size of droplets inside sprays were investigated near the nozzle orifice and were correlated with the needle valve lift of the injector nozzle. The L2F had a micro-scale probe which consists of two foci. The focal diameter was about 3µm, and the distance between two foci was 17µm. The data sampling rate of the L2F system was markedly high as 15MHz. Fuel sprays were injected intermittently into the atmosphere by using a common rail injector. The orifice diameter of the injector nozzle was 0.112mm and the rail pressure was 40MPa. The periods of solenoid energizing was set at 2.0ms. Measurement positions were located at 10mm downstream from the exit of the nozzle orifice. The results show that droplets mainly existed in the region off the spray center in the early injection period and concentrated at the spray center in the middle of injection period. Temporal changes in the number of droplets near the spray center were strongly affected by the needle lift and there in the relatively wide region were affected by the injection rate. Temporal changes in the droplet velocity near the spray center were strongly affected by the injection rate. The luminance distribution of the spray image was similar to the distribution of the number of droplets multiplied by the square of droplet size.

Key words: Laser-aided diagnostics, Atomization, Nozzle, Liquid droplet, Fuel injection, Diesel engine

Nomenclature

\[ t_1 \] time-of-flight between upstream and downstream foci
\[ t_2 \] time-of-scattering on the upstream focus
\[ t_3 \] time-of-scattering on the downstream focus
\[ S \] distance between two foci
\[ F \] focus size
\[ L \] focus length
\[ u \] velocity
\[ d_p \] droplet size
\[ T \] time after start of energizing the injector solenoid
\[ x \] coordinates in radial direction of spray
\[ z \] coordinates in axial direction of spray
1. Introduction

Higher thermal efficiency, lower exhaust emissions, and lower combustion noise are required for diesel engine. It is known that these requirements are in a trade-off relation. Controlling diesel combustion by using multiple fuel injection system is one of the most common way to accomplish these requirements. Research works on the combustion related to the multiple fuel injection have been conducted by many researchers. The effects of two-stage fuel injection on the UHC and CO emissions were investigated by varying the dwell between the two injections as well as the fuel quantity in each injection (Li, et al., 2010). A combination of ultraviolet-visible optical diagnostics was applied to the combustion chamber of a diesel engine in order to study the multiple fuel injection (Mancaruso, et al., 2008). The understanding of post injections for soot reduction in diesel engines was reviewed (O’Connor and Musculus, 2013).

Detailed information about fuel sprays is needed for further improvement of combustion, because the multiple injection utilizes sprays with different needle lift conditions. The needle lift affects the fuel flow inside the nozzle. It is known that the fuel flow turbulence inside the nozzle sac enhances the spray breakup. Cavitating flow within diesel injector passages had been investigated numerically using the homogeneous equilibrium model (HEM) (Lee and Reitz, 2010). Lee et al. concluded that there was some optimum lift profile in the needle closing movement. Schlieren visualization tests had been performed for a prototype diesel common rail direct-acting piezoelectric injector (Payri, et al., 2013). Payri et al. confirmed that the needle lift played a determinant role in the spray development, especially at the early stages of injection process. The transient flow and cavitation characteristics during oil drainage process had been investigated by numerical simulation under several needle lift condition (Sun, et al., 2015). A flow visualization experiment system with a transparent scaled-up multi-hole injector nozzle tip was setup for validating numerical simulation of cavitating flow in the nozzle (He, et al., 2013). Cavitation developing upstream and inside the diesel micro-channel orifices of transparent multi-hole fuel injector nozzles was characterized by using a high speed visualization system (Mitroglou, et al., 2014). A study was conducted about the influence of the needle lift on the internal flow and cavitation in diesel injector nozzles by CFD (Salvador, et al., 2013). It is understood that the cavitating fuel flow inside the nozzle and its variation with needle lift affect the spray behavior outside the nozzle.

Optical techniques have been used for the non-intrusive measurements of the inner structure of diesel fuel sprays. Droplet size distributions in sprays injected from a single-hole nozzle were measured by a laser diffraction particle analyzing system (Chen, et al., 2013). Experimental studies on diesel fuel sprays were carried out in a constant volume bomb to investigate the atomization and mixing process by applying the phase doppler anemometry (PDA) (Pribicevic and Sattelmayer, 2012). The spatial distribution of fuel mass in the near-nozzle region was investigated by using X-ray for understanding the effect of the shape of nozzle hole inlet on the spray characteristics (Im, et al., 2009). In spite of intensive research activities, there are a few knowledge about the relationship between the microscopic structure inside diesel fuel sprays and injection condition.

Based on the measurement of time-of-flight when a droplet flies between two foci, the velocity of droplet is obtained by a laser 2-focus velocimeter (L2F). The L2F has a high optical signal-to-noise ratio, so an effect of multiple scattering of droplets on the spray measurement is small even in high number density sprays. The L2F methods were applied to measure droplets inside the breakup length (Schugger, et al., 2000, Chaves, et al., 2001). The authors showed that the velocity and the size of droplets can be simultaneously obtained by adding the measurement of time-of-scattering to the L2F (Ueki, et al., 1994). The measurement of the velocity and size of droplets was successfully conducted by the developed L2F at 0.5 mm downstream from nozzle orifice (Ueki, et al., 2004). The temporal changes of the spray tip penetration near the nozzle orifice observed by macroscopic images were related to the size of droplets inside sprays measured by the L2F (Komada, et al., 2013).

In the previous study (Komada, et al., 2014), effect of the needle lift on spatial and temporal changes of droplet number, velocity, and size were discussed under three injection periods. In this study, the injection duration was set at 2.0ms when the period of the valve full open state was relatively shorter than the period of the valve movement state. The effect of temporal changes of valve movement on the temporal changes of diesel spray characteristics, especially the number and velocity of droplets were investigated.
2. Experimental setup

2.1 Fuel spray measurement system

The light probe of the L2F consists of highly focused two laser beams as shown in Fig.1. When a droplet flies through both upstream and downstream foci, time-of-flight \( t_1 \), time-of-scattering \( t_2 \) on the upstream focus and time-of-scattering \( t_3 \) on the downstream focus are measured. The velocity of a droplet is obtained by dividing the distance between two foci \( S \) with the measured time-of-flight \( t_1 \),

\[
u = \frac{S}{t_1} \tag{1}
\]

The relation used for the estimation of droplet size is that the ratio of the time-of-flight and the time-of-scattering corresponds to the ratio of the distance between two foci \( S \) and the droplet size \( d_p \) plus the focus size \( F \). The time-of-scattering can be estimated by averaging \( t_2 \) and \( t_3 \). The droplet size \( d_p \) can be estimated by

\[
d_p = u \cdot \frac{(t_2 + t_3)}{2} - F \tag{2}
\]

The diameter \( F \) of the focus was about 3\( \mu \)m, and the distance \( S \) between two foci was 17\( \mu \)m. The length \( L \) was about 20\( \mu \)m in the direction of optical axis. It can be mentioned that the L2F used in the present study had a micro-scale probe.

Figure 2 shows the fuel spray measurement system. A common rail injector was used to control the time, duration and pressure of injections. The clock signal with a frequency of 6MHz was used for recording the time when the L2F data was acquired. This was equivalent to 0.17\( \mu \)s time window for each data. The \( z \)-axis was the spray axis. Two foci of the L2F probe were set in a way that the direction from the upstream focus to the downstream focus was parallel to the spray axis. The light source was a semiconductor laser which has a maximum power of 100mW and a wave length of 808 nm. A non-spherical lens which had a focal length of 8 mm and a numerical aperture of 0.5 was adopted as the condenser lens. By the optical system with a length of 350mm including the light source, the light backscattered from a droplet at the focus was guided to a Si-APD (Silicon Avalanche. Photo Diode), and it was converted into an electrical signal. The time-of-flight and time-of-scattering were measured by the digital counter which was mainly constituted of an FPGA (Field Programmable Gateway Array) with a clock frequency of 480MHz. The maximum data sampling rate of the L2F system was 15MHz.

![Fig. 1 Measurement probe of L2F](image1)

![Fig. 2 Fuel spray measurement system](image2)
2.2 Experimental conditions

Table 1 shows the experimental conditions. The number of holes of the injector nozzle was 8, and the diameter of the nozzle orifice was 0.112mm. One of the 8 spray plumes was measured by the L2F while the remaining 7 spray plumes were deflected and collected. The rail pressure was set at 40MPa. The injector energizing duration was 2.0ms, and the injection interval was 1000ms. Simultaneous measurements of the velocity and size of spray droplets were conducted at 10mm downstream from the exit of the nozzle orifice. The ambient temperature was 296±6K. The injection quantity was 5.3mg/injection. The needle was fully opened at about one third of the injection duration.

The measurement was conducted during 10-150 injections. The number of droplets observed was 20,000 at each measurement position. The condenser lens was cleaned after it was misted by droplets of diesel fuel in several tens of injections. Table 2 shows the measurement positions which were located at an even distance from each other.

Spray images were taken by using a lamp with a lighting time of 180ns. Figure 3 shows spray images at $T=0.6$, 1.0, 1.5 and 2.0ms. $T$ indicates the time after start of energizing the injector solenoid. The measurement section of $z=10$mm was shown as a solid line. The deep color indicates high luminance. At $T=0.6$ms in the early injection period, the spray spread to the radial direction. The spray at $T=1.0$ms was narrower than that at $T=0.6$ms. A low luminance region appeared near the measurement section which was shown by the arrow. The sprays at $T=1.5$ms and $T=2.0$ms were narrower than that at $T=1.0$ms. The spray at $T=2.0$ms was brighter than the spray at $T=0.6$ms at the measurement section.

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Hole diameter (mm)</th>
<th>0.112</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of holes</td>
<td>8</td>
</tr>
<tr>
<td>Injection intervals (ms)</td>
<td>1000</td>
</tr>
<tr>
<td>Energizing duration (ms)</td>
<td>2.0</td>
</tr>
<tr>
<td>Rail pressure (MPa)</td>
<td>40</td>
</tr>
<tr>
<td>Ambient pressure (MPa)</td>
<td>0.1</td>
</tr>
<tr>
<td>Ambient temperature (K)</td>
<td>296</td>
</tr>
</tbody>
</table>

Table 2 Measurement positions

<table>
<thead>
<tr>
<th>$x$</th>
<th>-1.2, -0.9, -0.6, -0.3, 0, 0.3, 0.6, 0.9, and 1.2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>10 (mm)</td>
</tr>
</tbody>
</table>

Fig. 3 Spray images; $T=0.6$ms, 1.0ms, 1.5ms, and 2.0ms. (The arrow shows the local low luminance region.)
The luminance of spray images was evaluated from 0 to 255. Figure 4 shows the spatial distribution of the luminance on the measurement section of $z=10\text{mm}$ at $T=0.6$, 1.0, and 1.5ms in the early injection period. The luminance was within the measurable range. The spray periphery was defined as the radial position where the luminance took 10% of the maximum. As a result, the spray width was 3.8mm, 2.2mm, and 1.6mm at $T=0.6$, 1.0, and 1.5ms respectively.

### 2.3 Cross-correlation coefficient

A cross-correlation coefficient is utilized for evaluating the effect of temporal changes of injection conditions on the temporal changes of the spray characteristics. The cross-correlation coefficient was defined as;

$$
 r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} 
$$

In the formula, $x$ and $y$ are any two parameters of injection conditions and spray characteristics, that is, the needle lift, injection rate, number of droplets, and velocity of droplets. $\bar{x}$ and $\bar{y}$ indicate average values of each parameter.

### 3. Result and discussion

#### 3.1 Temporal changes in velocity and size of droplets

Figure 5 shows the temporal changes of the probability density of needle lift, injection rate, and number of droplets per injection at $x=0$ and 0.9mm. The needle valve lift increased in an approximately constant increasing rate in a period from $T=0.3$ms to $T=1.4$ms, and decreased in an approximately constant decreasing rate from $T=2.3$ms to $T=3.2$ms. The number of droplets at $x=0$mm had a single peak at $T=1.5$ms. The number of droplets at $x=0.9$mm had two peaks at $T=1.1$ms and $T=2.9$ms. Therefore, the temporal changes of the needle lift was similar to the temporal changes of number of droplets at $x=0$mm more than the temporal changes of the number of droplets at $x=0.9$mm. The injection rate rapidly increased in a period from $T=0.3$ms, when the needle valve start moving, to $T=0.7$ms. The injection rate took almost maximum at $T=0.7$ms, before the needle valve was fully opened. It is suggested that the injection rate was limited by the orifice throttle. The injection rate rapidly decreased in a period from $T=2.9$ms to $T=3.2$ms.

Figures 6(a) and (b) show the time resolved plots of velocity and size of droplets on $x=0$mm. The number of plots is 1000. Low velocity droplets appeared at the middle of injection in Fig.6(a). Most of droplets were smaller than 30µm in Fig.6(b).
Fig. 5 Temporal changes of the probability density of the number of droplets per injection, needle lift, and injection rate

Fig. 6 Time resolved plots of velocity and size of droplets; x=0mm

Fig. 7 Temporal changes of velocity
Figure 7 shows the temporal changes of velocity. White diamond and white square indicate the mass weighted average velocity of droplets at each measurement position of \( x = 0 \text{mm} \) and \( x = 0.9 \text{mm} \). The velocity of liquid fuel at the nozzle exit was calculated from the time-dependent injection rate. The velocity was plotted by black squares taking into account the time delay of the liquid fuel from the nozzle exit to the measurement section. The velocity based on the injection rate agreed with the average velocity of droplets in the periods from \( T = 0.6 \text{ms} \) to \( T = 0.8 \text{ms} \) and \( T = 2.9 \text{ms} \) to \( T = 3.4 \text{ms} \), and was higher than the average velocity of droplets at the middle of injection. It is thought that droplets which were injected in the period of low injection rate were included at the middle of injection as shown in Fig. 6(a).

Figure 8 shows the arithmetic mean size of droplets in every time window of 0.1ms. The size of the droplet near the spray center rapidly decreased in the period from \( T = 0.6 \text{ms} \), when a droplet appeared at a measurement position, to \( T = 0.7 \text{ms} \). The droplet size increased in the period from \( T = 0.7 \text{ms} \) to \( T = 1.8 \text{ms} \) near the middle of the injection period. It might be caused by the decrease of turbulence in the sac of injector nozzle. Small size droplets existed at the spray periphery on the middle of the injection period.

The size of droplet was averaged over the spray cross section. Figure 9 shows temporal changes of the cross-sectional averaged size of droplets and the spray width. The spray width decreased in the period from \( T = 0.6 \text{ms} \) to \( T = 1.5 \text{ms} \), and increased until the end of injection. The cross-sectional averaged size of droplets decreased in a period from \( T = 0.6 \text{ms} \) to \( T = 0.7 \text{ms} \), and increased in a period from \( T = 0.7 \text{ms} \) to \( T = 1.3 \text{ms} \). And it took a nearly constant value in a period from \( T = 1.3 \text{ms} \) to \( T = 3.0 \text{ms} \). It is thought that the droplet size at \( T = 1.3 \text{ms} \) was larger than the droplet size at \( T = 0.7 \text{ms} \) because the turbulence in the sac of injector was small in the case of the large lift of needle valve. A cross-correlation coefficient was utilized for evaluating the effect of temporal changes of spray width on the temporal
changes of the droplet size. The cross-correlation coefficient was calculated except the data at \( T = 0.6 \) ms because \( T = 0.7 \) ms was a cusp or singular point of curvature on the temporal changes of cross-sectional averaged size of droplets. The cross-correlation coefficient was -0.72. An inverse correlation was observed between the spray width and the droplet size. It should be mentioned that the cross-correlation coefficients could be affected by the fuel injection duration.

### 3.2 Effect of needle valve lift on velocity and number of droplets

The cross-correlation coefficient between the temporal changes of the needle valve lift and that of the number of droplets evaluated at each measurement position. The cross-correlation coefficient between the temporal changes of the needle valve lift and that of the number of droplets was shown in Fig. 11 by the square marks, and was 0.9 around the spray center. The cross-correlation coefficient became smaller toward the spray periphery, and had negative values at \( x = -1.2 \) and 1.2 mm. Namely, effect of the temporal changes of the needle valve lift on the number of droplets strongly appeared at the spray center. The cross-correlation coefficient between the temporal changes of the injection rate and that of the number of droplets was shown in Fig. 9 by the diamond marks, and was 0.7 near and around the spray center. Namely, the temporal changes of the number of droplets was affected by the injection rate in the relatively wide region inside the spray.
Figure 11 shows the cross-correlation coefficient between droplets velocity measured by L2F and the velocity based on injection rate. The cross-correlation coefficient was 0.8 at the spray center. And, the cross-correlation coefficient at the spray periphery was lower than that at the spray center. Namely, the effect of the injection rate on droplet velocity appeared near the spray center.

3.3 Spatial distribution of number of droplets

Figure 12 shows the spatial distribution of the number of the droplets per injection at $T=0.6$, 1.0, and 1.5ms in the early injection period. There were a few number of the droplets across the measurement section at $T=0.6$ms just after the spray arrived at the measurement positions. There were a lot of droplets both at the $x=-0.6$ and 0.6mm at the early injection period of $T=1.0$ms. There was a low luminance region inside the spray at $T=1.0$ms in Fig.4 as shown by the arrow. It is understood that the number density of droplets was low inside the spray. The similar luminance distribution was recognized in the spray images in other research articles. An inversed shadowgraph with sub-micron resolution of non-additive fossil diesel spray has been taken under 40MPa injection pressure and atmospheric ambient pressure (Crua, et al., 2012). The low luminance regions, in which the number density of droplets could be relatively low, were seen inside the spray. The diesel spray shadowgraphs under 40MPa injection pressure have taken by using a lamp with a lighting time of 30ns (Adam, et al., 2009). There were high luminance regions in which the number density of droplets could be relatively low. The number density of droplets inside the spray was not always higher than that at the spray periphery. There were a lot of droplets at the spray center at the middle of injection period of $T=1.5$ms.

It is thought that the luminance is the summation of the scattered light from droplets in the direction of line of sight of the spray. Figure 13(a) shows a comparison of the probability density distribution of luminance of the spray image and the probability density distribution of the summed number of droplets multiplied by the square of droplet size in the direction of line of sight at $T=1.0$ms. Both the luminance of the spray image and the number of droplets multiplied by the square of droplet size were almost constant and higher in a range from $x=-0.5$mm to 0.6mm.

The case of $T=1.5$ms is shown in Fig.13(b). The luminance distribution of the spray image was similar to the distribution of the number of droplets multiplied by the square of droplet size.
4. Conclusions

A laser 2-focus velocimeter (L2F) was applied for the measurement of diesel fuel sprays injected from a common rail injector at a rail pressure of 40MPa. Measurement positions were located at 10mm downstream from the exit of the nozzle orifice. The velocity, size, and number of droplets were measured under the injector energizing duration of 2.0ms. Spray images were taken and compared with the L2F measurement data. Conclusions were as follows:

1. The droplets mainly existed in the region off the spray center in the early injection period and concentrated at the spray center in the middle of injection period.

2. The luminance distribution of the spray image was similar to the distribution of the number of droplets multiplied by the square of droplet size.
3. Temporal changes in the number of droplets were strongly affected by the needle lift near the spray center.

4. Temporal changes in the number of droplets were affected by the injection rate in a relatively wide region inside the spray.

5. Temporal changes in the droplets velocity were strongly affected by the injection rate near the spray center.

References


