Study of Heterogeneous Structure in Diesel Fuel Spray by Using Micro-Probe L2F*

Daisaku SAKAGUCHI**, Shohei YAMAMOTO**, Hironobu UEKI*** and Masahiro ISHDIA**

**Graduate School of Science and Technology, Nagasaki University,
1-14 Bunkyo-machi, Nagasaki 852-8521, JAPAN
E-mail: daisaku@nagasaki-u.ac.jp
***Faculty of Engineering, Nagasaki University

Abstract
A L2F (Laser 2-Focus velocimeter) was applied for the measurements of the velocity and size of droplets in diesel fuel sprays. The micro-scale probe of the L2F has an advantage in avoiding the multiple scattering from droplets in a dense region of fuel sprays. A data sampling rate of 15MHz has been achieved in the L2F system for detecting almost all of the droplets which passed through the measurement probe. Diesel fuel was injected into the atmosphere by using a common rail injector. Measurement positions were located along the spray axis at 10, 15, 20, 25, and 30 mm from the nozzle exit. Measurement result showed that the velocity and size of droplets decreased and the number density of droplets increased along the spray axis. It was clearly shown that the mass flow rate in the spray was highest near the spray tip and was lower inside the spray.

Key words: Breakup, Droplet, Velocity, Size, Number Density, Optical Diagnostics

1. Introduction
Detailed information of fuel sprays is needed for the suitable control of the combustion in diesel engines. Hayato et al.(1) reported spray characteristics, atomization, and penetration at a high temperature and high pressure ambient. Understanding the spray behavior near the nozzle orifice is indispensable for modeling droplet disintegration. An investigation based on imaging was conducted about the influence of the nozzle geometry on the spray near the orifice by Han et al.(2). Alan et al. (3) uses X-ray radiograph, which is capable of penetrating dense fuel sprays to probe the structure of the core region of sprays. A PDA (Phase Doppler Anemometer) simultaneously measures the velocity and the size of spray droplets. For example, a high pressure diesel spray was measured by using a PDA and the effect of injection pressure on the correlation between the velocity and the size of fuel droplets was clarified by Hung et al. (4). Cao(5) compared the droplet size distribution reported by Levy et al. (6) with the one obtained by a maximum entropy method. A droplet is unable to be identified in a high number density condition because of the multiple scattering due to a large probe volume of PDA. In spite of extensive studies by many researchers, the velocity and size of droplets near the nozzle are still unclear. It has been reported by Lacoste et al. (7) that the measurement of droplets at a position of 30mm from the nozzle was difficult because the number density was too high. A L2F (Laser 2-Focus velocimeter) has been practically developed by using its nature of high optical SN ratio to advantage in the flow measurement of centrifugal compressor impellers by Shodl(8). The L2F was applicable to the measurement of a turbulent diffusion flame because of its high optical SN ratio as reported by the authors(9). A L2F system has been developed for the velocity measurement.
of dense diesel sprays by Chaves et al.\(^{(10)}\). Their L2F had a forward-scattered optical arrangement and had the image of two foci with a diameter of 10µm and a separation of 60 µm. A L2F system was also used for the velocity measurement in the primary breakup zone at 0.1 mm from the nozzle exit by Schugger et al.\(^{(11)}\).

The special feature of the L2F used in the present study was that the measurement probe was constructed by using the lens that was designed to focus a laser beam to near the diffraction limit. The distance between two foci of the L2F was reduced to only 20µm dealing with high number density droplets in high pressure sprays. The velocity and size of droplets in the spray injected intermittently from a common rail injector have been measured at 10, 15, 20, 25, and 30 mm from the nozzle exit. The number density of droplets was estimated by using the instantaneous velocity, size, and time interval between droplet observations. The time variation of spatial distribution of mass flow rate was also examined.

2. Experimental Setup

2.1 Micro-Probe L2F

The measurement probe of the L2F consists of highly concentrated two foci. Two parallel beams are located in line with the flight direction of a droplet as shown in Fig. 1. The distance between two foci, length of the focus, and focus size are indicated with \(S\), \(L\), and \(F\) respectively. Figure 2 shows the time-of-flight and time-of-scattering of a droplet which passes through two foci. The upper part of Fig. 2 shows the cross-section of the measurement probe.

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

![Fig. 2 Time-of-flight and time-of-scattering](image2)

While a droplet flies through the upstream focus, a scattering light is observed. The time-of-scattering \(t_2\) is measured by the digital counter which is mainly constituted of a FPGA (Field Programmable Gateway Array) with a clock frequency of 160 MHz. The threshold of scattering light is set so as to detect a 1 µm droplet. The original signal processing circuit controls automatically the amplification rate of the Si-APD (Silicon Avalanche Photo Diode) output against a strong scattering light from a large droplet. The other light scattering signal is observed while a droplet passes through the downstream focus. The time-of-scattering \(t_3\) at the downstream focus is also measured independently of the \(t_2\) measurement at the upstream focus. The time-of-flight \(t_1\) is measured as the time interval between two light scattering signals. The velocity \(u\) of a droplet is calculated by dividing the distance \(S\) between two foci by the measured time-of-flight \(t_1\), that is,
The droplet size $d_p$ depends on the measured time-of-scattering $t_2$ as reported in the author's literature\textsuperscript{(12)}. The ratio of the time-of-flight $t_1$ and the time-of-scattering $t_2$ corresponds to the ratio of the distance between two foci $S$ and the droplet size $d_p$ plus the focus size $F$. Thus, the droplet size is calculated by the equation,

$$\frac{S}{t_1} = d_p$$

Figure 3 shows the flowchart for measurements of time-of-flight and time-of-scattering. The digital counter starts ticking the time-of-flight with the detection of scattering light at the upstream focus and ends ticking with the detection of scattering light at the downstream focus. Then, an up-and-down flag is stored with the counted value which gives us the velocity. When a new scattering light at the upstream focus is detected after a scattering light at the upstream focus being detected, an up-and-up flag is stored. The velocity is not calculated in the case of the up-and-up flag, because the droplet passes through only the upstream focus. The L2F recognizes the existence of a droplet at the measurement probe even if the up-and-up flag is given. The number of droplets which passes through the measurement probe, $NO$, is taken as the summation of numbers of both up-and-down events and up-and-up events.

The distance between two foci, $S$, was decided by the design of the beam splitter in the optical system of the L2F and was calibrated as 20 $\mu$m. The focus size was experimentally estimated by measuring the light intensity distribution of the focused beam on a plate. Further, the focus size was confirmed by measurements of the time-of-scattering of water droplets from a humidifier and oil droplets from a mist generator using the L2F. The focus size $F$ was then estimated as 3 $\mu$m. The length of the focus is needed for the estimation of the number density of droplets as shown later. The length of the focus was estimated as 20 $\mu$m in this optical system. The focus size and distance between two foci of ordinary L2F used for the measurement of turbomachine\textsuperscript{(8)} were about 10 $\mu$m and 400 $\mu$m respectively. The focus size and distance between foci were reduced to about 1/3 and 1/20 respectively.

### 2.2 Estimation of Number Density and Mass Flow Rate

Spatial dispersion of droplets in a high number density region is very important for understanding spray characteristics. The L2F records the time-of-flight, the time-of-scattering and the appearance time of each droplet at the measurement probe one after the other. A distance between droplets along the direction from the upstream focus to the downstream focus, $L_d$, can be estimated by,

$$L_d = u \cdot \Delta t$$

where $\Delta t$ is a time interval between droplets’ appearance and $u$ is an instantaneous velocity. The time interval $\Delta t$ between droplets’ appearance at the measurement probe was evaluated by using all droplets including both droplets with the up-down flag and the ones with the up-up flag. The instantaneous velocity of the droplet which had the up-up flag was evaluated by interpolating the velocities of droplets appearing before and after that droplet. It is expected that one single droplet exists in a volume of $L_d \cdot (L + d_p) \cdot (F + d_p)$, where $L$, $F$, and $d_p$ are the length of focus in the direction of laser beam, the focus size, and the droplet size respectively. The number density of droplet, $N_d$, is the number of droplets...
which exist within a unit volume. Therefore, the number density can be estimated as

\[ N_d = \frac{1}{(L_d \cdot (L + d_p) \cdot (F + d_p))} \]  

(4)

Assuming that droplets are dispersed isotropically a distance between droplets is estimated by

\[ L_i = \frac{1}{\sqrt[3]{N_d}} \]  

(5)

An important step towards understanding spray behavior is to estimate the mass flow rate during injection. The mass flow rate \( m_f \) estimated by using the number density can be written as

\[ m_f(z,t) = \rho \cdot V_p(z,t) \cdot u(z,t) \cdot N_d(z,t) \]  

(6)

where \( V_p \) is the droplet volume.

Figure 4 shows the system configuration of the L2F. The light source was a semiconductor laser with a maximum power of 100 mW and a wave length of 835 nm. The light from the semiconductor laser was transmitted into a parallel beam with a collimator lens, and was divided into two beams by a beam splitter prism. In order to form a micro-scale measurement volume, two laser beams were condensed into two foci by a non-spherical lens with a focal length of 8 mm and a numerical aperture of 0.5. The optical system had a backscattering alignment. The light scattering from droplets at the upstream focus was collected on a Si-APD (S2381 manufactured by Hamamatsu Photonics) through a collimating lens and a microscope objective. The light scattering at the downstream focus was observed by the other Si-APD. The diameter of the sensible area of the Si-APD was 0.2 mm and was equivalent to the diameter of the focus image transferred onto the surface of the Si-APD. The length of the optical system was 350mm including the light source.

Fig. 3 Flowchart of data acquisition in L2F

Fig. 4 System diagram of L2F
2.3 Fuel Spray Measurement System

A common rail injector was used to control the injection timing, injection duration and injection pressure. Figure 5 is the system of fuel spray measurement using the L2F. Diesel fuel pressurized by a high pressure pump was stored in a rail. This fuel was then injected intermittently into the atmosphere. The ambient temperature and pressure were 298±6K and 0.1MPa respectively. The tested injector nozzle had 5 holes. The hole diameter \( d \) was 0.113 mm. One of the 5 spray plumes was measured by the L2F while the remaining 4 plumes were shielded and sucked out through flexible pipes. The injection interval was 330 ms and the period of energizing the solenoid was 1.0 ms. The rail pressure was 70 MPa and the amount of injected fuel was 2.97 mg per cycle. The coordinate \( z \) is the distance from the nozzle tip along the spray axis. Two foci of the L2F probe were set in such a way that the direction from the upstream focus to the downstream focus was adjusted to the spray axis. Simultaneous measurements of the velocity and size of spray droplets were performed at 5 positions of \( z = 10, 15, 20, 25, \) and 30 mm as shown in Fig.6. Measurement position shifted in the \( x \)-direction about 0.2 mm. The time from the start of energizing the injector solenoid to the droplet’s appearance was counted with a clock frequency of 1.5 MHz.

3. Result and Discussion

3.1 Time Variation of Number of Data

The number \( N0 \) of droplets which passed through the upstream focus was set at 5,000. Figure 7 shows the time variation of number of data obtained at \( z = 20 \) mm. Data were acquired during 70 injections. The abscissa indicates the time from the start of energizing the injector solenoid. The data were allotted to each time window of 0.1 ms. The solid rectangular bar represents the number of data which have the up-down flag. In this case, droplets passed through both the upstream and downstream foci. Then the velocity and size were measured correctly. The grey rectangular bar indicates the number of data which has the up-up flag. Droplets passed through the upstream focus but did not pass through the downstream focus, so they did not give the velocity and size. The total number of data is the sum of the number of data with the up-down flag and the one with the up-up flag. Spray droplets were observed on and after 0.8 ms. It was confirmed by images taken by using a stroboscope that the L2F detected droplets just after the spray tip reached the measurement position. The number of data with up-down flag was quite lower than that of up-up flag at
0.8 ms. It is understood that highly concentrated droplets disturbed a droplet's sequentially passing through both foci and many data with the up-up flag were given. The number of invalid data with the up-up flag was larger than the one of valid data during injection.

![Graph](image)

**Fig. 7** Time variation of number of sampled data; \(z=20\text{mm}\)

### 3.2 Distributions of Velocity and Size of Droplets

Droplets which passed through both upstream and downstream foci were extracted from the flag contained in the data record as shown before in Fig. 3. Figure 8 shows the time history of velocities for 1st and 2nd injections respectively at \(z = 20\) mm. Number of data obtained was 49 within the 1st injection and 61 within the 2nd injection. The instantaneous sampling rate of valid data reached higher than 1 MHz. Rapid changes in droplet velocity could be traced by the high data rate sampling. Many velocity data were around 200 m/s in the period from 0.8 to 1.7 ms and decreased gradually after 1.7 ms. A period of high velocity is called the spray head and a period after that is called the spray tail\(^4\). The characteristic velocity estimated by the Bernoulli's equation is 409 m/s based on the rail pressure. A few velocity data reached 400 m/s and were far from 200 m/s. It is deduced that these velocities come from high number density droplets. A high velocity appears when two different droplets passed the upstream and downstream foci sequentially. It is understood that the temporal variation in velocities for the 1st and 2nd injections are similar. Large velocity deviations from velocities lower than 100 to velocities higher than 300 m/s are observed in the spray head. It is understood that large droplets penetrate the air maintaining their velocities and small droplets after disintegration decreased their velocities markedly. The velocity deviation leads the spreading of droplets.

Velocity data in a time range between 0.8 to 2.0 ms were extracted for representing both the spray head and the spray tail. Arithmetic mean velocity was calculated by using the velocity data allotted to a time window of 0.1 ms. Figure 9 shows the time variation of mean velocity for 5 positions of \(z = 10, 15, 20, 25,\) and 30 mm. The velocity in the period of spray head from 0.8 to 1.7 ms showed higher level compared to the one of spray tail from 1.7 to 2.0 ms. It is clearly seen that the velocity decreased gradually from \(z = 10\) to \(z = 30\) mm in the period of spray head. In the period of spray tail, the mean velocity at \(z = 10\) mm was lower than that at larger distance \(z\). It is understood that the marked decrease in droplet velocity due to the end of injection appeared near the nozzle earlier. Figure 10 shows the time dependent spatial distribution of arithmetic mean size. The droplet size decreased from \(z = 10\) to \(z = 30\) mm in most of the injection duration expect the period from 0.8 to 0.9 ms. As the spray tip was located at about 25 mm in the period from 0.8 to 0.9 ms, it is understood that large droplets passed by small droplets and appeared near the spray tip.
Fig. 8 Time history of instantaneous velocity; $z=20$mm

Fig. 9 Time dependent spatial distribution of mean velocity

Fig. 10 Time dependent spatial distribution of mean size
3.3 Distributions of Number Density and Mass Flow Rate

Figure 11 shows the time variation of mean number density within a time window of 0.1 ms. Although the temporal change in the number density in the period of spray head was not so small, it is identified that the number density decreased gradually with time. The number density in the spray tail region at 5 measurement positions equally increased once and decreased. It is deduced that the increase in number density came from the decrease in the spreading of droplets. Because the marked decrease in the mean velocity as seen in Fig.9 suppresses droplets' deformation and disintegration in the spray tail, velocity deviations decreased as seen in Fig.8. Figure 12 shows the probability density distribution of the number density for a period from 0.8 to 1.3 ms. The open circle mark shows the probability density at \( z = 10 \) mm and the solid circle mark shows the case at \( z = 30 \) mm. These are estimated by all data with both the up-up flag and up-down flag within a window of 5000 1/mm³. The probability density of the number density at \( z = 30 \) mm was higher than that at \( z = 10 \) mm in the domain where the probability density is higher than 65,000 1/mm³. As droplets appear randomly at the measurement position, the probability of the time interval \( \Delta t \) between droplets' appearance shows mostly constant. It is understood from equations (3) and (4) that the number density is inversely proportional to \( \Delta t \). The probability density distribution of the number density substantially has a peak at a small number density.

Fig. 11 Time variation of number density

Fig. 12 Probability density of number density; time=0.8-1.3 ms
Figure 13 shows the probability density distribution of the distance $L_i$ in a period from 0.8 to 1.3 ms. All the data based on both the up-up and up-down flags were used. The peaks in probability density at 5 measurement positions were seen at the distance $L_i$ of 20 - 30 μm. The dotted line indicates the distance between two foci of L2F. The distance $L_i$ was estimated at an order of the distance between two foci. It is understood that droplets with
less \( L_i \) than the distance between foci existed and the lowest value of \( L_i \) was estimated at about 5 \( \mu m \).

Figure 14 shows the time dependent spatial distribution of the number density at \( z = 10, 15, 20, 25, \) and 30 mm within a time window of 0.1 ms. Although the spatial and temporal changes in the number density was not so small, it is understood that the number density increased along the spray axis in the spray head region. The increment of number density comes from the decrease in droplet size along the spray axis as shown in Fig.10.

Figure 15 shows the spatial distribution of mass flow rate. The mass flow rate attained the maximum at the time range from 0.8 to 0.9 ms. This means that the number density at spray tip was highest. The images of spray reconstruction from series of X-ray absorption measurement reported by Powell et. al.\(^{(13)}\) have shown a similar result.

4. Conclusion

A laser 2-focus velocimeter (L2F) with a micro-scale probe has been upgraded further for measurements of velocity, size, and appearing time of droplets in a high number density region of diesel fuel sprays. The rate of data acquisition of the measurement system has been increased to 15 MHz. Measurement were performed at 5 positions 10 to 30 mm from the nozzle exit. The rail pressure of the common rail injector was 70 MPa. The results are as follows;

(1) Time-resolved measurements of velocity and size were performed successfully with a data sampling rate higher than 1 MHz.
(2) The velocity and size of droplets decreased along the spray axis.
(3) The distance between droplets in isotropically dispersed condition was estimated at an order of the distance between two foci.
(4) The number density increased along the spray axis.
(5) The fuel mass was concentrated near the spray tip.

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References


