1. INTRODUCTION

Characteristics of spray disintegration near the nozzle orifice dominate atomization and combustion of fuel droplets. Enhancement of atomization has been achieved by the decrease in nozzle orifice diameter and increase in injection pressure. Tanabe et al. reported the control of fuel injection rate based on such as multi-stage injection for promoting the exhaust emissions reduction [1]. In the multi-stage injection, the injection rate when the needle valve is fully opened decreases while the injection rate under the condition of transient needle opening or closing increases, compared with the single-stage injection. Blessing et al. have utilized visualized images of the flow inside the orifice for understanding the effect of needle opening on spray characteristics [2]. Understanding of the spray behavior near the nozzle orifice is indispensable for the initial condition of the modeling of droplet disintegration. Han et al. conducted an investigation about the influence of the nozzle geometry on the spray near the orifice by picture measurement [3]. Vuorinen et al. have used X-ray for the measurement of fuel mass in the spray near the nozzle of a high-pressure diesel injector [4]. Phase Doppler anemometer (PDA) can measure simultaneously the velocity and size of spray droplet. Hung et al. measured a high pressure diesel spray by using a PDA and clarified the effect of injection pressure on the correlation between the velocity and size of fuel droplet [5]. Cao [6] compared the droplet size distribution reported in the literature [7] with the calculated droplet size distribution by KIVA-2 code. In spite of extensive studies by many researchers, the velocity and size of droplets near nozzle orifice are still unclear. Lacoste et al. have reported that the measurement of droplet at a position of 30mm from the nozzle exit is difficult because the number density is too high or a liquid core might exit [8].

Shodl has developed a laser 2-focus velocimeter (L2F) practically by using its nature of high optical SN ratio to advantage in the flow measurement of centrifugal compressor impeller [9]. The authors have confirmed that L2F is applicable to the measurement of a turbulent diffusion flame because of its very high optical SN ratio [10]. Chaves et al. have developed a L2F system for the velocity measurement of dense diesel spray [11]. Their L2F is forward scattered type and the image of two foci have a diameter of 10μm and a separation of 60μm. Schugger et al. used a L2F system for the velocity measurement in the primary breakup zone at 0.1 mm from the nozzle exit [12]. The special feature of the L2F used in the present study is that the laser beam is concentrated to near the diffraction limit. The distance between two foci of the L2F is reduced to only 20μm in anticipation of higher number density in a common rail high pressure spray. By using this micro-prove L2F, the velocity and size of droplets in the spray injected intermittently from a common rail injector was measured in the core region near the exit of the injector nozzle.

2. EXPERIMENTAL SETUP

2.1 Advanced laser 2-focus velocimeter

In order to measure the droplets in the core region of fuel spray with high number density using a laser velocimeter, one of important techniques is to avoid multiple scattering. The feature of the L2F used in the present study is that the focal diameter is reduced to near the diffraction limit. Figure 1 shows the measuring volume consisting of two foci. The diameter F of the focus is about 2 μm, the distance S between two foci is 20 μm and the length L is about 50 μm in the direction of optical axis. The focal diameter and distance between two foci of ordinary L2F used for the measurement of turbomachine [13] was about 10 μm and 400 μm respectively. The focal diameter and the distance between foci were reduced to about 1/5

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ABSTRACT A laser 2-focus velocimeter (L2F) has been applied for the measurements of velocity and size of droplets in the core region of diesel spray. The L2F has a micro-scale probe which consists of two foci. The focal diameter is about 2 μm, and the distance between two foci is 20 μm. The feature of this L2F is that the focus is reduced to near the diffraction limit. Investigated was the fuel spray injected into the atmosphere intermittently from a 5-hole injector nozzle with the orifice diameter of 0.16 mm. The injection pressure was set at 100 MPa by using a common rail system. Measurements were conducted on the plane where the axial distance was 20 mm from the orifice exit. Valid data were extracted by a conditional sampling method based on the fact that a droplet passes through both the upstream and downstream focus. Valid data was only about 30% of the acquired data in the injection period because the number density was so high. The velocity and size of droplets showed the highest value at the spray center and decreased at off-axis positions. It is clearly seen that the velocity and size has a nearly uniform distribution at first half of injection period, and varies spatially at later half of injection period.
and 1/20 respectively. The distance $S$ between two foci is reduced by about half compared to the one of 36 $\mu$m in the author's previous study [14].

Figure 2 illustrates the measurement principle of the velocity and size of droplet. When a droplet flies through two foci, a light scattering signal is observed while the droplet passes through the upstream focus. The time-of-scattering $t_2$ is measured by the digital counter which is mainly constituted by a programmable logic device (Altera, EPM7128LC84-7) incorporating binary counter ICs with the clock signal of 64 MHz. The threshold of scattered light is set to a level in which a 1 $\mu$m droplet can be detected. The original signal processing circuit restricts the amplification rate for APD output automatically 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 $t_3$ on the downstream focus is also measured independently of the $t_2$ measurement on the upstream focus. The time-of-flight $t_1$ is measured as the time interval of two light scattering signals. The velocity of a droplet can be easily calculated by dividing the distance $S$ between two foci by the measured time-of-flight $t_1$, that is,

$$u = \frac{S}{t_1} \quad (1)$$

The droplet size is estimated by the measured time-of-scattering $t_2$ as reported in the author's literature [15]. 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 $dp$ plus the focus diameter $F$. The droplet size can be estimated by the equation,

$$dp = u \cdot t_2 - F \quad (2)$$

The droplet which passes through the upstream focus does not necessarily pass through the downstream focus. When the number density of droplet is very high, local droplet distance is sometimes shorter than the distance between two foci. In such a case, the droplet other than the one that passes through the upstream focus will pass through the downstream focus. Then, the time-of-flight is not measured correctly. When the flight direction of a droplet is fluctuating, the droplet which passes through the upstream focus sometimes differs from the droplet which passes through the downstream focus. The data obtained by such a different droplet should be deleted. Figure 3 shows the flowchart for the time-of-flight and time-of-scattering measurements. Counting of clock signal for the time-of-flight starts by the detection of an upstream signal and stops by the detection of a downstream signal and an up-and-down flag is saved with counted value. When an upstream signal is detected before detecting a downstream signal, then an up-and-up flag is saved with counted value. The number of data sampling $N0$, which corresponds to the number of droplets passing through the upstream focus, is set before the beginning of the measurement. The total number of data $N0$ is 10,000 at each measurement condition in the present study. Validity data can be extracted after the measurement by referring to the flag contained in the data.
The different droplet data by the flight direction fluctuation might be left behind to the data of up-and-down flag. However, this different droplet data produced when the distance between droplets is comparatively long is removable as the data of unusually long time-of-flight.

2.2 Configuration of L2F

Figure 4 shows the system configuration of L2F. The semiconductor laser with the 100 mW maximum output is used as a light source. This semiconductor laser is an infrared type with a wave length of 835 nm. The light emitted from the semiconductor laser is changed into parallel light with a collimator lens, and is divided into two beams by a beam splitter prism. In order to form a small measurement volume, two laser beams are condensed to two foci by the non-spherical lens with a focal length of 8.0 mm and a numerical aperture of 0.5.

Back-scattered light from a droplet at each focus is led independently to a separate Si-avalanche photodiode (APD; S2381 manufactured by Hamamatsu Photonics) through a collimating lens and microscope objective. The diameter of the sensible area of the APD is 0.2 mm and this diameter is equivalent to the diameter of the focus image expanded with the collimating lens and microscope objective. The cut-off frequency of the APD is 1GHz to a load resistance of 50 Ω. The length of the optical system is 350mm including the light source.

The scattered light is converted to an electric signal by the APD and is led to the signal analyzer consisted of the counter for time-of-flight and time-of-scattering measurements. The signal analyzer has a timer which counts the time when a time-of-flight datum is acquired. The data of time-of-flight and time-of-scattering are stored simultaneously in a personal computer through a digital interface. The number of the data sampled, which corresponds to the number of droplets passing through the upstream focus, is set before the beginning of the measurement. The number of data is 10,000 in the present study.

2.3 Accuracy of droplet size measurement

Droplet size estimation by the time-of-scattering measurement is effective also to a non-globular droplet. However, droplet size might be underestimated when a focus crosses near the end of a droplet. The related study [16] has been reported by Simmons, et al. that the droplet size was estimated from the chord length, which is the crossing distance on a droplet and is less than the droplet diameter in most cases. In order to estimate the error in droplet size measurement, a droplet is assumed to be a spherical form. Since the position crossed by the focus on a droplet is located randomly, the probability density of droplet size can be estimated from the probability density of chord length. When a focus crosses near the center of a droplet, the chord length becomes close to the diameter and there is little change in the chord length by the change of the crossing position. On the other hand, when a focus crosses near the end of a droplet, the chord length becomes shorter than the diameter and change of the chord length by change of crossing position is remarkable. Therefore, the probability density of chord length near the diameter is high, and the probability density of chord length underestimated is low. The probability density distribution of the chord estimated statistically and geometrically is shown by the dotted curve in Fig. 5. The droplet size estimated from the average of the dotted curve is about 80 % of the droplet diameter. Although the probability density of short chord is low, the skirt of probability density distribution spreads to the droplet size zero. By removing the data with probability density lower than about 5% of the peak probability density, as indicated by the single dot and dashed line of 0.015, the probability density distribution can be corrected to the solid curve. The droplet size, which is on the right hand side of the hatched line, can be estimated at 90% plus-or-minus 10% of droplet diameter. It is understood that underestimation does not influence the mean droplet size and droplet size distribution so much.

As the ratio of time-of-scattering at each focus, $t_2 / t_3$, should be the order of unity, the measurement of $t_3$ is effective for the noise reduction of velocity data as suggested by the authors [17] in case of a conventional L2F. In the present study, only the time-of-scattering $t_2$ at the upstream focus is used for estimating the droplet size. The time-of-scattering $t_3$ at the downstream focus is used for estimating the correlation between $t_2$ and $t_3$. Data are removed as noise derived from different droplets when the ratio of $t_2$ and $t_3$ is out of the range between 0.5 and 2.0. The result of probability density of droplet size hardly changes if $t_3$ or the average value of $t_2$ and $t_3$ is used.
2.4 Fuel spray measurement system

Figure 6 shows the fuel spray measurement system by the L2F. Diesel fuel pressurized by a high-pressure pump was supplied into a common rail and injected into the atmosphere intermittently by a 5-hole injector nozzle with the hole diameter $D$ of 0.16 mm. The injection interval was 330 ms. The coordinate $z$ is taken from the nozzle orifice exit in the direction of injection. The coordinate $x$ is taken from the center to the periphery of the spray in the optical axis of the incident laser beam. Simultaneous measurements of the velocity and size of spray droplet were conducted on the plane of $z = 20$ mm. Measurement position is $x = -0.5, 0.0, 0.5,$ and $1.5$ mm. The rail pressure was set at 100 MPa. The clock signal with the frequency of 100 kHz was used for recording the acquisition time of L2F data, and the acquired data were allotted into the time interval window of 0.01 ms. The injection duration was 1.0 ms.

3. RESULTS AND DISCUSSION

3.1 Droplet detection in spray core

Figure 7 shows the temporal variation of the number of detected droplets allotted into the time interval window of 0.2 ms. The transverse axis, Time, is measured from the instant when the control voltage is impressed to the injector solenoid. Four marks of circle, square, triangle, and lozenge indicate cases for the measurement position $x$ of -0.5, 0.0, 0.5, and 1.5 mm respectively. The total number of sampled data was 10,000, and data were accumulated for about 500 - 1500 injections. Droplets were observed on and after Time = 0.8 ms at positions of $x = 0.5$ and 0.0 mm. No droplet was observed before this period. It is understood that droplets reached the measuring position on 0.8 ms after the start of control voltage impression. The droplet observed on and after 1.0 ms at the position of $x = 1.5$ mm. Because the injection duration was 1.0 ms, the main spray corresponding to the injection duration is thought to appear from 0.8 ms to about 2.0 ms. Droplets in the spray tail might be observed after 2.0 ms. It is easily understood that the number of observed droplet corresponding to the injection duration is higher for the spray center. On the contrary, the number of observed droplet in the injection duration decreased markedly at $x = 1.5$ mm. The reason for the difficulty in the droplet measurement at large $x$ might be that the incident laser beam or scattered light is disturbed by highly atomized droplets. Wavelike variation is observed obviously after 5.0 ms at $x = 1.5$ mm. Further investigation would be needed to make clear whether this wave shows some vortex structure in a spray.

As the number of observed droplets decreased after 2.0 ms, the discussion is concentrated to the droplets corresponding to the injection period from 0.8 to 2.0 ms. Figure 8 shows the spatial distribution of the number of conditionally sampled data. The triangle mark shows the number of observed droplets in the injection period. As seen in Fig.7, number of events is larger at the spray center. Droplets which passed through both the upstream and downstream focus can be extracted from the flag contained in the recorded data as shown before in Fig.3. The square mark indicates the number of droplets which passed through both upstream and downstream focus. Only about 30% of the data measured in the injection duration had the up-and-down flag indicating that one particle passed through both foci sequentially. It is deduced that the spatial distance between the two droplets is shorter than the distance between 2 foci in many cases. The solid circle mark indicates the number of droplets which have the ratio of $t_2$ and $t_3$ being in the range between 0.5 and 2.0. The number of valid data is about 10 % of the acquired data in the injection period.
Figures 9 (a), (b), (c), and (d) are the probability density distribution of substantial data rate at the positions of $x = -0.5, 0.0, 0.5,$ and $1.5$ mm respectively. The triangle mark is the data rate estimated from the original data extracted in the injection period corresponding to the triangle in Fig.8. It is understood that the instantaneous data rate is restricted to about $5$ kHz, and this is because the data acquisition procedure shown in Fig. 3 takes time. The probability density distribution of the data at $x = -0.5$ and $0.0$ mm has a sharp peak near the data rate of $5$ kHz. The probability density distribution at $x = 0.5$ mm has also a peak near the data rate of $5$ kHz and decreases gradually in lower data rate side. The skirt of the distribution spreads to a quite low frequency. The lozenge mark connected with dotted line indicates the probability density distribution for the noise-reduced record, which is sampled conditionally based on that a droplet passed both foci and time-of-scattering at each focus is nearly equal. This corresponds to the solid circle mark in Fig.8. The probability density near the data rate of about $5$ kHz is removed markedly and the one with the data rate of about $2$ to $3$ kHz increased relatively. Because there was a little number of the data at $x = 1.5$ mm, the noise-reduced data rate could not estimated.

Figure 10 shows the spatial distribution of the substantial data rate. The circle mark indicates the mean value of the probability density distribution of data rate for all measured data at each measurement position. The mean data rate is around $2$ to $3$ kHz. The data rate in the period from $0.8$ ms to $2.0$ ms indicated by the triangle mark increases to about $5$ kHz which is the upper limit of the present data acquisition system. The data rate of noise-reduced record decreases again to about $3$ kHz.
3.2 Velocity and size of droplets

Figure 11 shows the temporal variation of mean velocity in a time interval window of 0.2 ms. Velocities are plotted only in the period of injection, because the number of data decreases due to noise reduction after 2.0 ms. Velocity at four measurement position has a little difference in the first half of the injection period, however a marked difference appears in the latter half of the injection period. This might be related to the fact that the region of spray is narrow at the early period in the injection period and expands later.

Figure 12 shows the temporal variation of arithmetic mean droplet size. The difference in droplet size between measurement positions from 1.0 to 1.4 ms is not remarkable. However, it is clearly seen that the droplet size varies spatially from 1.6 to 2.0 ms. And this tendency of temporal and spatial variation of arithmetic mean size is similar to the one of mean velocity.

Figure 13 shows the spatial distribution of mean velocity and arithmetic mean droplet size in the injection period from 0.8 to 2.0 ms. It can be seen that the velocity is highest at the spray center and droplet size decreases in the spray off-axis region.

3.3 Correlation between velocity and size

Figures 14 (a), (b), (c) and (d) show the joint probability density distribution associated with velocity and size at the positions $x = -0.5, 0.0, 0.5, \text{and} 1.5 \text{ mm respectively.}$ The solid curve is the bag breakup criteria; $We_D>12,$ and the dotted curve is the boundary layer stripping criteria; $We_D/Re_D^{1/2}>0.5$ as previously described by Hung et al. [5]. The velocity of droplet itself is adopted as the reference velocity in the present paper, because it is not easy to estimate the relative velocity between each droplet and surrounding air. This means that the surrounding air velocity is assumed to be negligible. A part of droplets have higher velocity and larger size than curves of bag breakup criteria and boundary layer stripping criteria at the spray center. Probability density of these unstable droplets with higher velocity and larger size than breakup criteria curves decreased remarkably at $x = 1.5 \text{ mm}.$

4. CONCLUSIONS

A laser 2-focus velocimeter (L2F) with a semiconductor laser has been developed for the simultaneous measurements of velocity and size of fuel droplets in the core region of diesel spray from a common rail injector at rail pressure of 100 MPa. Valid data were extracted by a conditional sampling method based on the fact that a droplet passes through both the upstream and downstream focus. The concluding remarks are as follows,

(1) The measurement of velocity and size of fuel droplet was successfully conducted in a quite dense spray at 20 mm downstream from nozzle exit. However, valid data was only about 30% of the acquired data in the injection period because the number density was so high.

(2) Velocity and size of droplets shows the highest value at the spray center and decreases at off-axis positions.

(3) The velocity and size has a nearly uniform distribution at first half of injection period, and varies spatially at later half of injection period.

(4) A part of droplets have higher velocity and larger size than bag breakup and boundary layer stripping criteria at the spray core by the joint probability density distribution associated with velocity and size. The probability density of these unstable droplets decreases at off-axis position.
5. NOMENCLATURE

- $D$: diameter [mm]
- $m_f$: mass of fuel [kg]
- $\alpha$: spray angle [deg]
- $D$: diameter of nozzle orifice [mm]
- $dp$: diameter of droplet [$\mu$m]
- $F$: diameter of focus [$\mu$m]
- $L$: length of focus [$\mu$m]
- $N_0$: number of measured droplet passing through upstream focus [-]
- $Re_D$: droplet Reynolds number [-]
- $S$: distance between two foci [mm]
- $t_1$: time-of-flight [\mu$s]
- $t_2$: time-of-scattering at upstream focus [\mu$s]
- $t_3$: time-of-scattering at downstream focus [\mu$s]
- $We_0$: droplet Weber number [-]
- $x$: coordinate in the direction perpendicular to injection [mm]
- $z$: coordinate in the direction of injection [mm]

6. REFERENCES


