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Development of Quantitative Measurement of Fuel Mass Distribution Using Planar Imaging Technique

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Abstract : The quantified fuel mass distribution of a spray was obtained from laser induced fluorescence images with optical patternation. In the dense spray region, however, the emitted fluorescence signal is significantly attenuated in the path of the detector because of particle scattering. Thus, the fluorescence image obtained with a camera may be different from the true fluorescence image pattern. Therefore, we propose a method of finding the geometric mean of the intensities obtained with two cameras and apply it to a solid-cone spray. We also compared this optical patternation technique with other spray measurement techniques, such as, PDPA (Phase Doppler Particle Analyzer) and the mechanical patternator, to validate the accuracy of the proposed method. Results show that the quantified mass distribution of the optical patternator agrees well with those of the PDPA and the mechanical patternator. Hence, we can estimate the local mass distribution rapidly without determining the entire structure of the spray by using the geometric mean of the signals obtained from two cameras.

Keywords : Laser induced fluorescence (LIF), Imaging method, Spray, Mass distribution, Signal Attenuation.

1. Introduction

In most practical applications of atomization system, the symmetry of the spray pattern produced by an atomizer is an important variable in most practical applications. In gas turbine combustors, fuel must be distributed uniformly to provide not only high combustion efficiency but also low pollutant emission (Lefevre, 1989). Unless spray asymmetry is severe, it may not be detected by visual inspection. Hence, the quantitative determination of patternation is desirable, not only in nozzle design and development, but also for quality control in specific applications (Tate, 1960). For decades, to obtain spray pattern, mechanical patternators have been used, featuring an array of collection tubes or sections (McVey et al., 1987). However, mechanical patternator has a limited spatial resolution and induces the perturbation in the two-phase flow field. To overcome such disadvantages of the mechanical patternator, a non-intrusive method using planar laser imaging technique was developed. Wang et al. (1997) measured the spray pattern of the air-blast atomizer using Mie scattering. Su et al. (1998) used LIF image corrected with the measured Mie scattering image to investigate a transient fuel spray. McDonell and Samuelsen (1997) studied fuel distribution by PLLIF (Planar Liquid Laser Induced Fluorescence) method. Sankar et al. (1999) obtained not only the spatial distribution of fuel mass, but also the planar distribution of the Sauter Mean Diameter (SMD). This optical patternation provides a non-intrusive, high-resolution, and quantitative measurement of spray distribution. Moreover, LIF signal is proportional to the mass of the fuel, and thus, it is advantageous for quantitative imaging of fuel distribution in sprays.

However, there are several problems in obtaining quantitative spray distribution. Especially, in dense sprays, quantitative interpretation can be significantly affected by the attenuation of the incident laser sheet and the attenuation of the emitted fluorescence signal by scattering from particles in the path of the detector (Talley et al., 1996). Su et al. (1998) and Talley et al. (1996) introduced the bidirectional illumination and the sequential illumination methods, respectively, in the optical patternation of spray to address the attenuation of the incident laser sheet. Sick and Stojkovic (2001) measured the transmission of the signals passing through an entire spray region, and quantified the attenuation of the LIF signals in their path through the hollow-cone spray.

This study aims to find the method for obtaining quantitative information of fuel mass distribution. We examined a solid-cone spray with relatively uniform distribution, and focused on the correction of the attenuations of the incident laser sheet and the emitted fluorescence signal.

2. Experiments

2.1 Measurement Theory

The intensity of the fluorescent signal depends on the concentration of fluorescing molecules (Talley et al., 1996; Zelina et al., 1998; Le Gal et al., 1999). Thus, the fluorescent signal intensity from a droplet is proportional to the cube of the droplet diameter, if the droplet is a sphere. In other words, the fluorescent signal intensity is proportional to the volume of droplet, that is, to the mass of droplet, when the fluorescing materials are distributed uniformly in the test fluid and do not vary in composition such as on the evaporation of droplets. The intensity of the fluorescent signal detected on a CCD pixel, $G_f(x, y)$ can be expressed as follows:

$$G_f(x,y) = c_f I_0(x,y) \sum N_i(x,y) d_i^3(x,y) \qquad (1)$$

where $I_0(x, y)$ is the intensity of the incident light at (x, y), N_i is the number of the droplets of the i-th size class d_i, and c_f is the coefficient that depends on fluorescence and detection efficiency, experimental parameters, and so on. The fluorescent signal intensity indicates the total volume of drops, which exist inside the volume during the camera exposure time: i.e., spatial volume (or mass) concentration of liquid drops. However, coefficient c_f is difficult to obtain, so that we can only obtain the relative distribution of the fuel mass concentration from the experiment.

To obtain the mass flux data from the fluorescent intensity, we have to know the size and the velocity of each drop. For a non-evaporation and non-reacting case, the mass flow rate of each cross section will be constant regardless of time when there is no vaporization. Therefore, the mass flux, $\dot{m}''$ can be expressed as follows (Lee et al., 1999; Jung et al., 2003):

$$\dot{m}''(x,y) = \frac{G_f(x,y)\bar{v}_{v.w.}(x,y)}{\sum\limits_x \sum\limits_y G_f(x,y)\bar{v}_{v.w.}(x,y)} \frac{\dot{m}}{A} \quad [\mathrm{g/cm^2 sec}] \quad \text{where} \quad \bar{v}_{v.w.} \equiv \frac{\sum N_i d_i^3 v_i}{\sum N_i d_i^3} \qquad (2)$$

(a) (b)

Fig. 1. The solid-cone nozzle used in experiments: (a) components of spray nozzle and (b) instantaneous image of spray.

where, v_i is the velocity normal to the measurement plane, $\bar{v}_{v.w.}$ is the volume weighted velocity, $\dot{m}$ is the mass flow rate of the nozzle, and A is the area of one CCD pixel. In case of the like-doublet injector spray, the velocity of the drops can be calculated by using the jet injection velocity and the geometry of the spray, assuming that the radial velocities of drops are same as the jet injection velocity (Jung et al., 2003). The volume weighted velocity can be also calculated experimentally by using the size and velocity information of each drop obtained from PDPA.

2.2 Test Conditions

A solid-cone spray was used to obtain uniform volume distribution. The atomizer (*UniJet* nozzle) was manufactured by Spraying Systems Co., and consisted of a disc, a core, a slotted strainer and body parts as shown in Fig. 1(a). A continuous Ar-ion laser (Spectra-Physics Model 2020, 3W) was used as the light source, and the laser beam was formed into a sheet with sheet beam probe optics (Dantec). The laser sheet was horizontal and orthogonal to the axis of the spray, and a camera (Sony, DSC-D700, 1344 × 1024) was located perpendicular to the direction of the laser sheet to capture images. The spray was injected vertically under atmospheric condition. The test fluid was contained in a surge tank, which can endure up to 40 bar, and was pressurized with N_2 gas for pressure stabilization. The pressure difference was measured upstream of the fuel nozzle by a pressure gauge. The orifice diameter of nozzle was 0.79 mm and the water flow rate was 10 g/sec when pressure difference was 5 bar. Figure 1(b) shows the instantaneous image of spray at this pressure condition. To provide fluorescence intensity proportional to the volume of the liquid, methanol/water solution containing 30 mg/l fluorescein dye (Aldrich F245-6, $C_{20}H_{12}O_5$) was used as a test fluid (Jung et al., 2003). The fluorescence image was obtained by using 550 nm long wave pass filter to measure the mass distribution. The variation of laser sheet can be corrected by including a known concentration reference in each image (van Cruyningen et al., 1990). For this purpose, the argon-ion laser excited the quartz cell filled with the test fluids. The fluorescence images of the quartz cell were used to obtain the mean intensity profile of the laser sheet. The fluorescence images of the spray were then divided by this mean intensity profile to correct the non-uniform intensity distribution of the laser sheet. The two cameras were positioned perpendicularly to the direction of the two laser sheets. As shown in Fig. 2, it was impossible to take images from the position directly below the injector owing to the obstacles (e.g., drain, drops on the window) when measuring the radial distribution of the spray. Thus, the camera had to be inclined to a certain angle. However, this oblique positioning of the camera leads to perspective distortion of the images. To correct this perspective error, all images were processed using the affine transformation (Raffel et al., 1998). When the square-grid plate was placed inside the measurement cross-section, the square image was recorded as a general four-sided

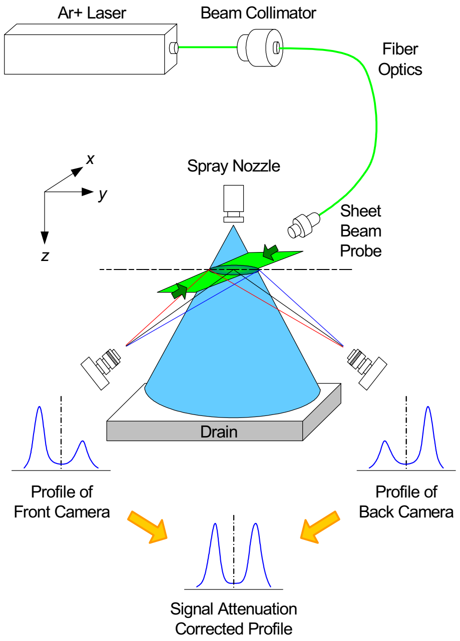


Fig. 2. Schematics of experimental setup and definition of coordinate system. In the dense spray (hollow cone type), the intensity distribution is affected by the signal attenuation between test section and camera.

polygon image because of the perspective error. Hence, the parameters for the affine transformation can be determined by finding the mapping function that converts the recorded trapezoidal image into the real square grid.

3. Results and Discussion

3.1 Correction Method for Signal Attenuation

The spray used in this study was so dense that the incident laser sheet was attenuated through spray. To overcome this effect, two counter-propagating sheets illuminated the spray in sequence; the first was from one direction and the second was in the same plane but originating from the opposite direction. To make the two laser sheets pass through the same spray cross section, we placed a calibration grid plate inside the illumination plane with guide rails, and then steered the sheet beam probe optics precisely to illuminate the calibration grid plate. The reference plate was also used to image this calibration grid plate for the affine transformation. Since the spray used in this study was in steady state, it was assumed that two sequential images obtained from right-illuminated and left-illuminated beams represented the same fuel distribution reasonably. After obtaining the images, we calculated the geometric mean intensities from two sequential images; we multiplied the intensity of the left-illuminated image with that of the right-illuminated image for each pixel and took the square root. This method was first suggested by Talley et al. (1996). If two counter-propagating sheets are used, the total attenuation of opposing rays from each sheet must be the same since the attenuation path is the same. If we take the geometric mean of two images, the intensity of a laser sheet is the same at any given location along a given ray penetrating into the spray. Therefore, this method can be used to reconstruct the actual intensity of the incident laser beam.

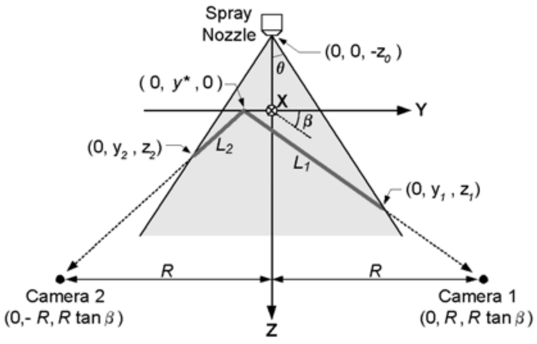


Fig. 3. Geometry of the beam path passing the uniform solid-cone spray, where R is the distance from spray axis (Z-axis) to the camera, and β is the viewing angle of the camera.

In addition to the attenuation of the incident laser beam, the fluorescent signal can be attenuated significantly through the dense spray because of the scattering from particles in the path between the laser-illuminated plane and the camera as shown in Fig. 2. Since the camera is inclined to a certain angle, the length of the signal path through the spray varies with each radial position. If the camera is placed in the $+Y$ plane, the attenuation path of a point on the $-Y$ axis is longer than that on the $+Y$ axis. Therefore, the symmetric spray pattern can be measured as an asymmetric pattern with respect to the camera position.

Figure 3 shows the path of the beam passing the uniform solid-cone spray whose angle is 2θ. In this figure, the X-axis is the path of the incident laser beam, Z-axis is the direction of the spray injection, and cameras are placed symmetrically at (R, R tanβ) and ($-R$, R tanβ). R is the distance from spray axis (Z-axis) to the camera, and β is the viewing angle of the camera. If we detect a signal of a location, (y^*, 0), the sum of the two lengths of the signal path to be attenuated in a spray region, L_1+L_2, can be expressed as follows (Koh et al., 2003):

$$L_1 + L_2 = \sqrt{1+\tan^2\beta}\left[\frac{2z_0\tan\theta}{1-\tan\beta\tan\theta}\right] = const. \tag{3}$$

Since β, θ, and z_0 are fixed in Eq. (3), the sum of the two beam paths is the same at all points in the image plane. From Beer's law, the emitted signal intensity, G_0, is exponentially attenuated in traversing distance L through a spray region. The recorded signal intensity after passing through a spray region, G_t, is defined as follows:

$$G_t = G_0 \exp[-\gamma L] \tag{4}$$

where γ is the attenuation coefficient. This attenuation coefficient is the function of the number of particles per unit volume, the absorption and scattering cross sections (Bohren and Huffman, 1983). Thus, the attenuated signal intensity is affected by the number density and size distribution of the droplets, and the wavelength of scattered or fluorescent signal. If the attenuation coefficient varies slightly in the measurement region, such as in the uniform solid-cone spray, the corrected signal can be obtained from the geometric mean of the two intensities detected from the symmetric positions (subscripts 1 and 2) as shown in Fig. 3.

$$\sqrt{G_1G_2} = G_0\exp\left[-\frac{\gamma}{2}(L_1+L_2)\right] \cong K_{ext}G_0 \tag{5}$$

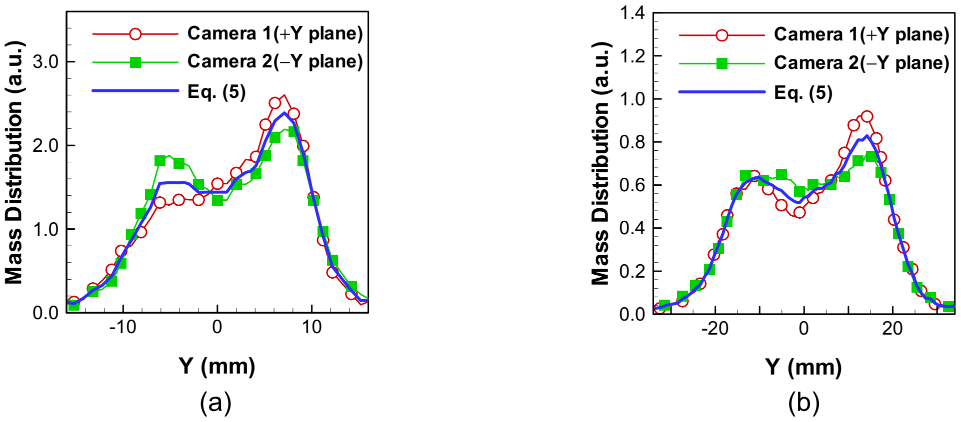


Fig. 4. Mass distribution from optical patternator at (a) 25 mm and (b) 50 mm downstream from the nozzle tip. Eq. (5) indicates the geometric mean of two intensities obtained from the two camera locations.

where G_0 is the emitted signal intensity at a measurement point, G_1 and G_2 are the intensities of the attenuated signals detected on camera 1 and camera 2, respectively, and K_{ext} is a coefficient that depends on the attenuation coefficient, γ, and path length, L. In case of a solid-cone spray, the attenuation coefficient, γ, is assumed to be constant, because the mass distribution is relatively uniform in the cross-section. Since the sum of the signal paths, $L_1 + L_2$, is also constant at $X = 0$, the exponential term is substituted with the constant, K_{ext}, and the original signal intensity can be found by using the geometric mean of the two intensities in solid-cone spray. However, the attenuation coefficient may not be constant in the entire region of the spray, although $L_1 + L_2$ is constant at $X = 0$. For example, for a hollow-cone spray, the attenuation coefficient is not constant because the signal attenuates significantly in the thin edge of the spray boundary. Furthermore, the sum of signal paths, $L_1 + L_2$, is not constant when the measurement plane is $X \neq 0$ (Koh et al., 2003). Thus, K_{ext} may not be constant throughout the measurement cross-section, and this geometric mean value, $\sqrt{G_1 G_2}$, may not provide the exact information of the fluorescence signal using Eq. (5). However, this correction method can be used to obtain the qualitative profile in dense spray, at least.

Figure 4 shows the radial profiles of the fuel mass distribution at two axial positions, $Z = 25$ mm and $Z = 50$ mm. At $Z = 25$ mm, although the intensity of the fluorescent signal at the measuring plane is the same, the mass distribution measured from the camera of the $+Y$ plane is significantly different from that of the $-Y$ plane due to the attenuation effect depending on the camera position.

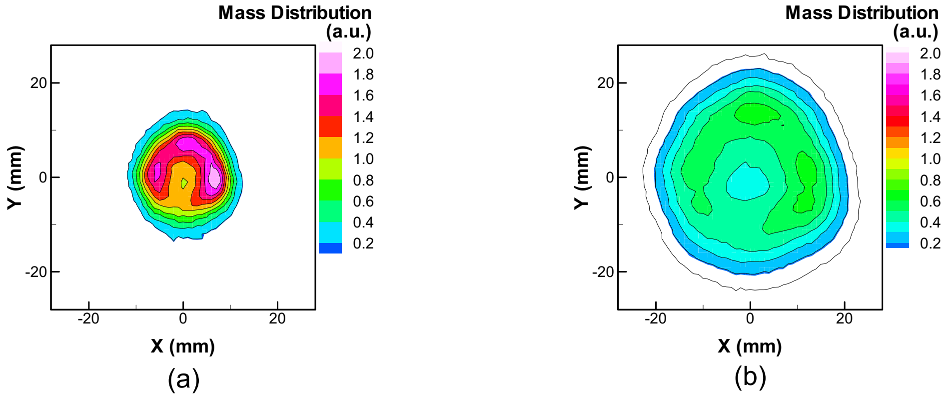


Fig. 5. Planar fuel mass distribution of solid-cone spray at (a) 25 mm and (b) 50 mm downstream from the nozzle tip.

The distribution measured from the camera of the $+Y$ plane shows that the high density of the fuel existed in the $+Y$ position. On the other hand, the distribution measured from the camera of the $-Y$ plane shows that two peaks of the high density fuel exist near the center of the spray. However, the corrected mass distribution using Eq. (5) indicates that the solid-cone spray shows relatively uniform distribution around the center, but has a slightly dense region in the $+Y$ position. At $Z = 50$ mm, the deviation of the mass distribution between the two camera positions become smaller, and the corrected mass distribution shows that the spray is distributed more uniformly as the axial distance (Z) increases.

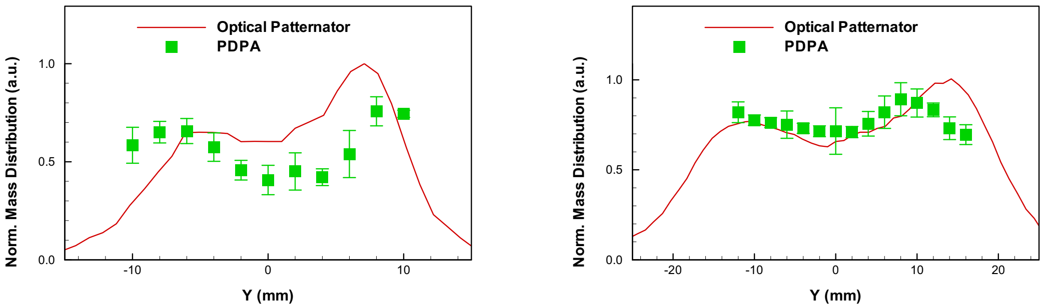
Figure 5 shows the quantified images of the mass distribution obtained by using Eq. (5) at each axial location from the nozzle. The higher mass distribution appears along a circumferential ring like a hollow-cone spray at $Z = 25$ mm and as the distance from the nozzle increases ($Z = 50$ mm), the spray is distributed more uniformly.

3.2 Comparison of Mass Distribution Measurements in Solid-Cone Spray

To verify the correction method for the signal attenuation, the exact spray pattern must be known. Therefore, PDPA was also conducted to determine the pattern of the solid-cone spray. Since the PDPA provides the joint measurement of drop size and velocity, the flux sensitive measurement (such as the PDPA, the mechanical patternator) can be converted into a corresponding concentration sensitive technique (such as the optical patternator) (McDonell et al., 1995). The concentration data was converted from the PDPA data, i.e., the number density, N, and the volume mean diameter, D_{30}. Figure 6 shows the local mass distribution measured by the optical patternator and the PDPA. The value of each measurement was normalized so that the sum of the concentrations has the same value throughout the entire measurement region of the PDPA.

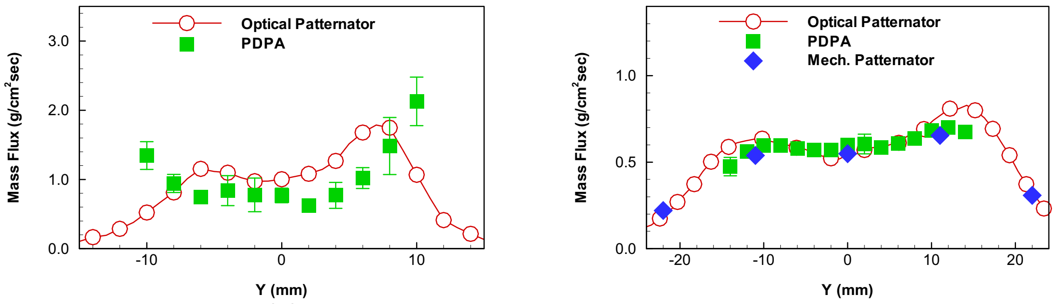
The mass distribution obtained from the PDPA in the center was much smaller than the mass distribution measured with the optical patternator, at $Z = 25$ mm. However, at $Z = 50$ mm, the PDPA agreed better with the optical patternator except for the right ($+Y$) peaks. The number density and the size distribution are subject to large errors since they depend upon accurate compensation for probe volume variation with size, total counting efficiency, and an accurate determination of velocity. Since several errors were associated with each other in the PDPA measurement, a large variance may be expected (McDonell et al., 1995). In this PDPA measurement, only about 65 % of the drops were validated at the center region of $Z = 25$ mm, while 85 % or more of the drops had valid size information at the whole region of $Z = 50$ mm. Hence, the difference in the mass distribution data between the PDPA and the optical patternator is believed to be due to the rejected information of 35 % of drops.

The patternation of the solid-cone spray was also performed using a mechanical patternator to compare its results with those of the non-intrusive optical method. The mechanical patternator consists of 180 (15 × 12) sampling tubes with a 10 mm × 10 mm square cross-section, and the sample



(a) (b)

Fig. 6. Comparison of mass distribution measured by the optical patternator with that of the PDPA at (a) 25 mm and (b) 50 mm downstream from the nozzle tip.



(a) (b)

Fig. 7. Comparison of mass flux of solid-cone spray at (a) 25 mm and (b) 50 mm downstream from the nozzle tip.

tubes are divided by a 1 mm thin lattice. Since the greater part of the sprayed liquid was collected in no more than 5 tubes at 25 mm downstream from the nozzle, the measurement of mass flux was only performed at 50 mm downstream to obtain the reasonable resolution.

The mass flux data calculated from the optical patternator were compared with those obtained with the PDPA. At Z= 25 mm, the mass flux data obtained with the PDPA indicate that the liquid mass is nearly uniform in the center region, and show the same tendency compared with the optical patternator. However, the mass is slightly larger at the spray boundary as shown in Fig. 7(a). At Z= 50 mm, the mass flux distribution data of the optical patternator were in good agreement with those of the PDPA. The mechanical patternator data are also shown in Fig. 7(b). Although the number of measured points was not sufficient due to the low spatial resolution of the mechanical patternator, the mass flux data obtained from the mechanical patternator were in good agreement with those of the PDPA and the optical patternator.

Although the velocities of droplets are considered in the mass distribution of the optical patternator, the relative errors are above ±50 % with respect to the mass flux of the PDPA at Z= 25 mm. The volume weighted velocity calculated from the PDPA data is thought to be insufficient for the transformation of the concentration data of the optical patternator. If the accurate velocity information is given, the mass distribution may be converted into the mass flux distribution, which can be compared to that measured by other flux-based instruments, such as the PDPA and the mechanical patternator.

4. Conclusions

The mass distribution of a solid-cone spray was obtained by using laser induced fluorescence signal since the fluorescent signal is proportional to the volume of droplet, i.e., to the mass of droplet. The quantitative data of the mass distribution and flux were obtained by correcting the attenuation of incident laser sheet and signals, and by using the several parameters, such as the volume weighted velocity, the mass flow rate of the nozzle, and the sum of the fluorescence intensity over the image of each cross section. To correct the signal attenuation in the path through the dense spray, the method to find the geometric mean of the intensities obtained from the two cameras was evaluated and verified. If the signal was attenuated asymmetrically due to the viewing perspective or the significant non-uniformity of the spray pattern, a single-image detection may not give accurate information on the local fuel mass distribution either quantitatively or qualitatively.

The mass distribution further downstream obtained from the optical patternation agreed quite well with the mass flux from the PDPA and the mechanical patternator. Although the correction method using two cameras was limited such that the attenuation coefficient remained constant in the spray region, the geometric mean of the signals obtained from the two cameras was used to estimate the local mass distribution rapidly without determining the entire structure of the spray. Since it is able to provide information on the 2-D plane within a relatively short time, it has strong advantages over the point measurement techniques such as PDPA.

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