APPLICATION OF SHADOW DOPPLER VELOCIMETRY TO ARBITRARY-SHAPED DROPLET MEASUREMENT IN WATER SPRAY

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Abstract

The shadow Doppler velocimetry (SDV) is employed for measurements of arbitrarily-shaped droplets in a water spray. In a region of the spray sufficiently far from the breakup region of liquid film, where most of droplets are spherical, the size-velocity correlation measurement result by SDV shows good agreement with that obtained by the improved interferometric laser imaging technique. The SDV can be also applied to the breakup region where considerable number of droplets are in irregular shapes, showing statistically in terms of a shape index that the population of such droplets are higher than in the region sufficiently far from it. The present paper also demonstrates the performance of SDV equipped with two parallel fiber-array sensors, which is effective for the measurements of droplet trajectory angles. The dependence of the angles on droplet diameters is presented, showing the larger inertia for the larger droplets. Furthermore, the stereoscopic measurement by two SDV optical systems is also conducted in order to capture the projection of droplet shapes from two different directions. The droplet shadows are observed in the breakup region at the edge of the spray cone. It can be found that, under the present measurement condition, the influence of the radial gradient of the axisymmetric mean spray flow on droplet shapes is not dominantly strong.

Introduction

In the research of liquid atomization sprays, the phenomena in the breakup region of liquid film into droplet pieces are of great interest. As for spray measurements, some excellent techniques in practical use have been developed so far, such as the phase Doppler anemometry (PDA [1]) and more recently, the improved interferometric laser imaging (ILIDS [2,3]). However, since theoretically they are valid for only spherical droplets, they can not be applied to the breakup region where measurable fractions of droplets are in irregular shapes.

In the present research, the "shadow Doppler velocimetry (SDV)" [4,5] is employed for water spray measurement, which can simultaneously measure velocity and size of particles or droplets. The distinctive feature of the SDV is its applicability to arbitrarily-shaped particles, and its measurement performance is not influenced strongly by particle optical properties. Therefore, even though so far it has been intensively applied to the research of pulverized coal combustion [6,7], it is also useful to various kinds of spray measurements. For example, it can be applied to pain spray measurements in which droplets are not always optically inhomogeneous [8], whereas it is also effective for the measurement of spray-drying [9] where their shapes and optical properties are unknown and changing through the process.

In the present paper, we assess the performance of SDV in water spray measurements, especially focusing on irregularly-shaped droplets. As for instrumental development of the SDV, after the first significant improvement in [4] and [5], the present authors have further improved the system so that the shadow images of particles with their velocity typically up to 100 m/s and their diameter larger than 5~10 μm can be acquired in 8-bit gray scale levels [10]. The purpose of this paper is to show the effectiveness of the improved SDV system for water spray measurements.

Furthermore, as advanced application examples, we employ the SDV with newly developed double fiber-array sensors [11]. By using the sensors, various kinds of measurements such as those of droplet trajectory angles and stereoscopic measurements are possible. In the present paper, the results of such advanced applications of SDV are also presented to demonstrate various possibilities of SDV applications.

Schematic of Experiments

The setup of the present SDV optics (SDPA Model 8250, KANOMAX Japan Inc.) is schematically illustrated in Fig.1. The droplet velocity is measured by the conventional laser Doppler velocimetry (LDV), while the sliced image of its shadow by two laser beams at each data-sampling moment is captured by a linear fiber-array sensor with 64 channels. The particle shape is reconstructed from those sliced images with the information of its velocity.

In the present system, the resolution of the shadow image has been greatly improved as described in the previous section. The sizing performance of the present SDV was reported by Matsuura et al. [10].

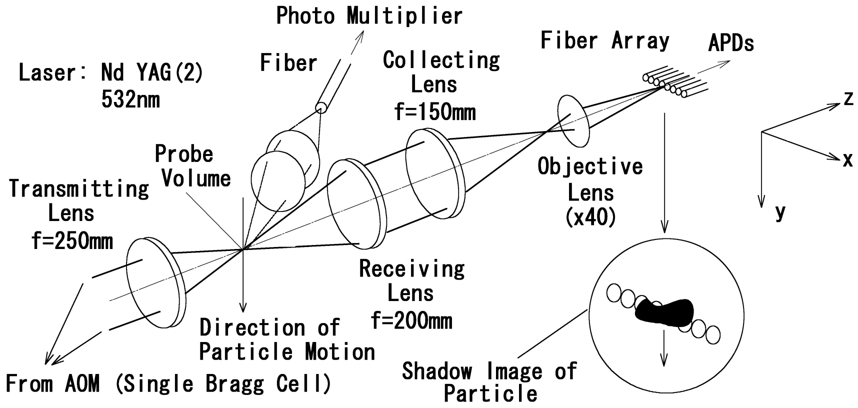

Figure 1. Schematic of SDV optics.

As for advanced application examples, we also applied the SDV with newly developed double fiber-array sensors [11] to the present water spray measurement. For these experiments, two of 32-channel fiber-array sensors were manufactured and installed instead of the normal single-line fiber-array sensor with 64 channels. Since the total number of the fibers is the same, the other SDV components including the signal processor can be utilized without any further modifications of the normal system.

The first example is the parallel 2-line fiber-array configuration as illustrated in Fig.2-a. By employing the configuration, the droplet trajectory angle $\phi = tan^{-1}(v_x/v_y)$ can be measured, where v_x and v_y are the components of droplet velocity vector in x and y directions (Fig.1), respectively; that is, we can obtain the direction of droplet motion by the fiber separation distance L and the displacement of the droplet shadow parallel to fiber-arrays Δx. For large trajectory angles, the relative position of the sensors in x-direction can be shifted at a distance of Δx_s so that whole particle shadow can be kept within the view areas of the both sensors.

The other configuration is for stereoscopic measurements. The optics is illustrated in Fig.2-b. Two SDV optical systems (Optics A: Transmitter A + Shadow Receiver A, and Optics B: Transmitter B + Shadow Receiver B) are installed with the angle between the two optical axes of 90 degrees. The centers of the probe volumes of both systems are carefully adjusted to coincide each other. Each of the two optical systems is similar to that shown in Fig.1, except the transmitters whose specifications are presented in Fig.2-b. As for Doppler signals, only those by the scattering of green light (Transmitter A, $\lambda=532nm$) are detected in the present experiment. For further details, see Ref.[11].

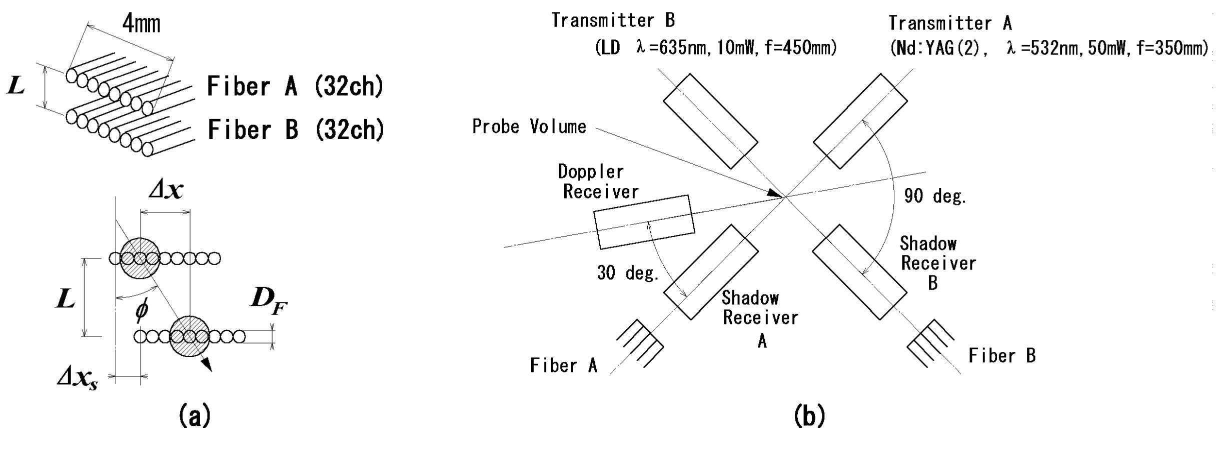

Figure 2. Double fiber-array SDV. (a) Parallel configuration for trajectory angle measurements. (b) Stereoscopic measurements.

In the present experiments, a Delavan spray nozzle (type 45-B, 0.50 GPH) was employed with the water pressure of approximately 0.8 MPa. The operating condition was chosen so that the results can be compared with those by Kobayashi [3].

Results and Discussions

First of all, in order to examine the performance of the present SDV in spray measurements, its result is compared with that of ILIDS by Kobayashi [3]. The SDV data used for comparison were integrated from those of nine probe positions in 10mm x 10mm planer measurement section as shown in Fig.3-a, to compare with the corresponding ILIDS result. The central location of the measurement section is 30 mm away from the nozzle exit, where most of droplets have already become spherical. Since the dynamic range of diameter measurement is different between each system, diameter-velocity correlation maps are compared in Fig.3-b and Fig.3-c rather than the other statistical expressions such as diameter histograms. The significant difference under 20 μm in diameter is simply due to the difference of dynamic range depending on the setup of both optical systems. Despite the result of the SDV showing slightly lower velocity for the same diameter than the ILIDS result, both correlation maps show fairly good agreement in the range between 30 and 80 μm.

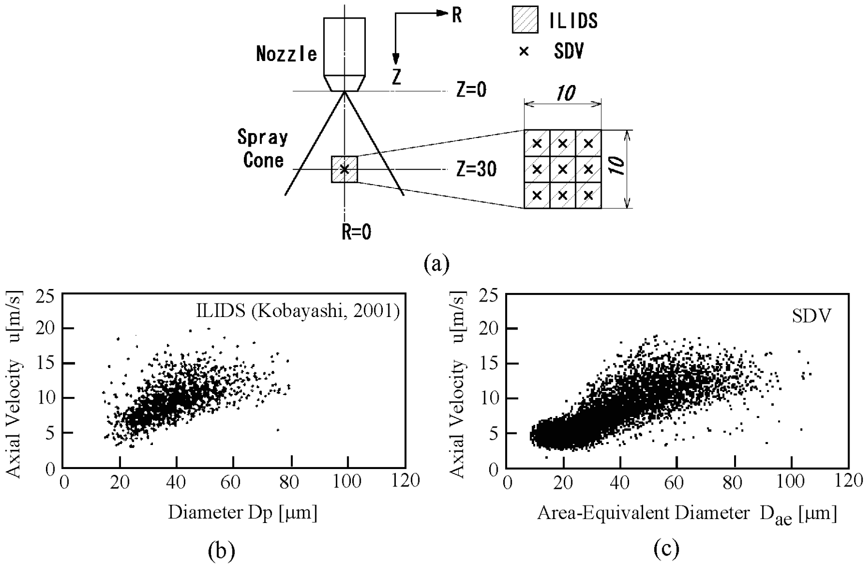

Figure 3. Comparison of diameter-velocity correlation by ILIDS and SDV. (a) Measurement section. (b) ILIDS result by Kobayashi (2001). (c) SDV result.

Secondly, the breakup region of water film, especially at the outer edge of the spray cone close to the nozzle exit is observed. Here, in order to keep the mean droplet motions as perpendicular to the fiber-array (*x*-direction) as possible, the nozzle axis is inclined as shown in Fig.4-a. Example shadow images in Fig.4-b show various phenomena occurring in the breakup region, such as complicatedly stretched water film, the moment of separation and the formation of droplets, and so on. The shapes of droplets completely separated from water film can be reconstructed successfully Fig. 4-c. The existence of irregularly-shaped droplets can be confirmed by the SDV.

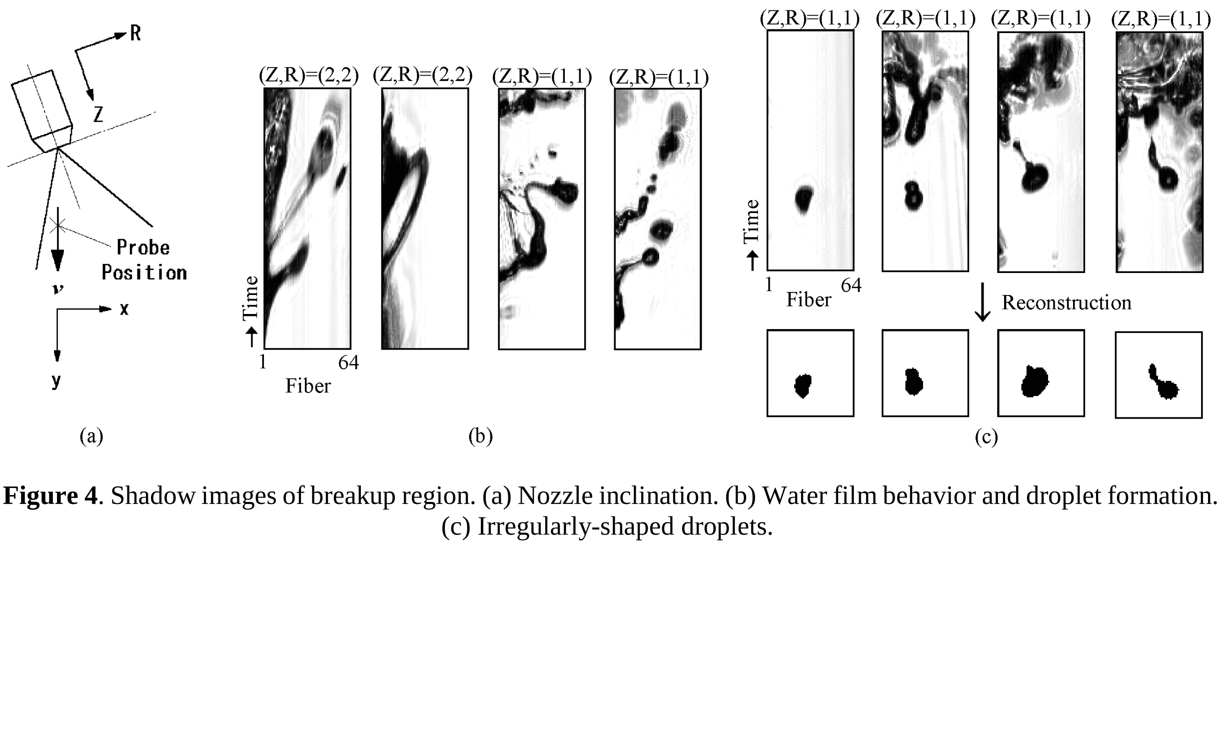

Figure 4. Shadow images of breakup region. (a) Nozzle inclination. (b) Water film behavior and droplet formation. (c) Irregularly-shaped droplets.

To show the fact that more irregularly-shaped droplets can be found in the breakup region than in the region far from it, the statistical approach is required. Here, we introduced a shape index φ defined by $\varphi = D_{ae} / F_y$, where D_{ae} is the area-equivalent diameter and F_y is the vertical Feret diameter as illustrated in Fig.5-a, respectively.

Even though the normal SDV with a single fiber-array sensor can potentially measure the droplet trajectory angles by using the method in Ref.[5], its accuracy is not always sufficient, especially for droplets passing through the right center of the probe volume with respect to the optical axis ("in-focus condition" [4]). This also causes the ambiguity in the reconstruction process of droplet shapes, which results in measurement uncertainty of the other frequently-used shape indices such as circularity. Since D_{ae} and F_y are not affected by the ambiguity, φ is an effective parameter especially for SDV measurements to describe statistical tendency. The results for two different locations are presented in Fig.5-b (far from the breakup region) and Fig.5-c (near the breakup region). It is clearly observable that most of droplets are spherical (φ =1) for the former case, whereas the existence of irregularly-shaped droplets is not negligible in the latter case, especially for large diameters. As the examples below, the measurable popularity of irregularly-shaped droplets in breakup region is also expressed by statistic approach.

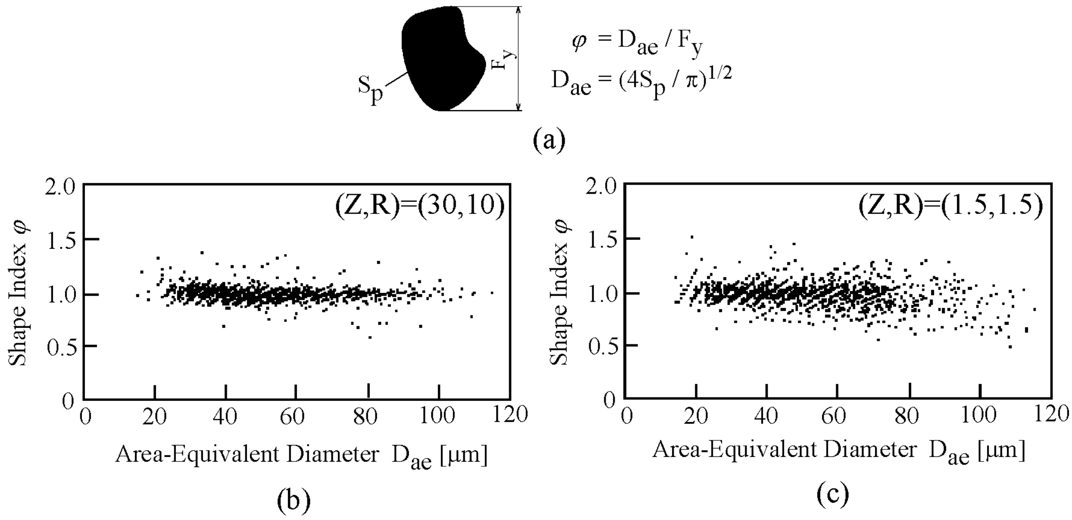

Figure 5. Irregularity of droplet shapes. (a) Definition of shape index. (b) Far from breakup region. (c) Near breakup region.

So far we assessed the performance of the SDV system equipped with the normal single fiber-array sensor. In the latter half of this section, we show the advanced application examples by employing the double fiber-array sensors. The first example is the trajectory angle measurement. As mentioned above, the accuracy of the trajectory angle measurement by normal SDV is not always sufficient. The 2-line parallel fiber-array configuration is more effective [11]. Figure 6 presents the measurement results of the trajectory angle. It shows the correlation between trajectory angles ϕ and droplet diameters D_{ae}. Most of data on the symmetric axis of the nozzle (Fig.6-a) are distributed around ϕ=0 degrees, except those under D_{ae}=20 μm, which may be due to the slight misalignment of the nozzle position. On the other hand, the trajectory angles are strongly correlated with droplet diameters for the positions far from the axis (Fig.6-b and Fig.6-c). This shows the fact that the larger droplets can keep inertia at the stage of droplet generation with relatively less effect of the surrounding spray flow field, compared with the smaller droplets.

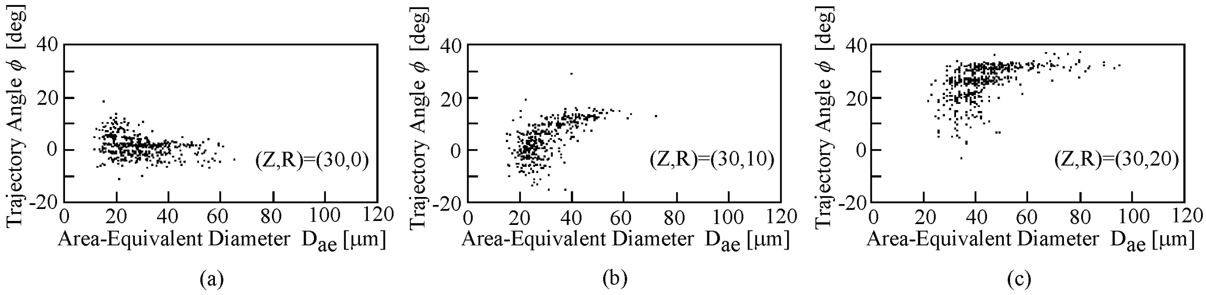

Figure 6. Correlation between diameter and trajectory angle measured by parallel double-fiber-array SDV.

(a) (Z,R)=(30,0). (b) (Z,R)=(30,10). (c) (Z,R)=(30,20).

The other advanced application example of the double fiber-array sensors is the stereoscopic observation of droplet shapes by SDV. Figure 7 shows the measurement results for the probe position (Z,R) =(2,2), at the outer edge of the spray cone. The setup is illustrated in Fig.7-a. Here, since the nozzle inclination in Fig.4-a is again introduced, the cross section of the spray cone on the plane including both optical axes is elliptic as in the figure. If the radial gradient of the axisymmetric mean flow properties influence considerably on droplet shapes, its effect may be stronger for the shape measured by Optics A than that by Optics B, so that the characteristic of projected droplet shapes observed by two optical systems are expected to be different. The example shadow images are presented in Fig.7-b, showing irregular shapes of droplets. However, distinctive characteristic difference is not found between the shadow projections measured by Optics A and Optics B. In the present measurement condition, it can be concluded that the influence of the radial gradient of the axisymmetric mean flow on droplet shapes is not dominantly strong.

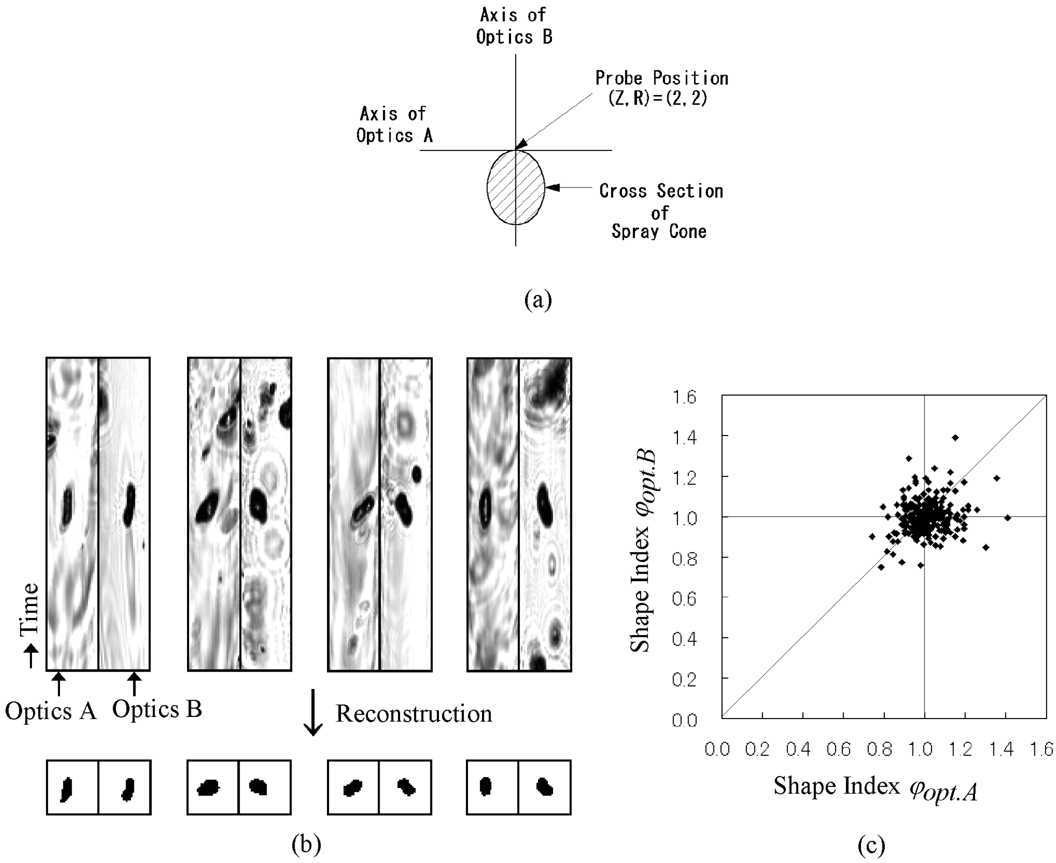

Figure 7. Stereoscopic measurement by SDV for the probe position (Z,R)=(2,2). (a) Probe position. (b) Shadow images. (c) Correlation between the shape indices by two SDV optical systems.

Summary

The shadow Doppler velocimetry (SDV) was employed for measurements of arbitrarily-shaped droplets in a water spray. In the region where most of droplets are spherical, the size-velocity correlation measurement result by SDV showed good agreement with that obtained by the improved interferometric laser imaging technique, confirming the applicability of the SDV to spray measurements. The SDV was also applied to the breakup region where considerable number of droplets are in irregular shapes, showing statistically that the population of such droplets were higher than in the region sufficiently far from it. The present paper also demonstrated the performance of SDV equipped with two parallel fiber-array sensors, which was effective for the measurement of trajectory angle of droplets. The dependence of the angle on diameter implied the larger inertia for larger droplets. Furthermore, the stereoscopic measurement by two SDV optical systems was also conducted in order to capture the projection of droplet shapes from two different directions. The droplet shadows were observed in the breakup region at the edge of the spray cone. It was found that, under the present measurement condition, the influence of the radial gradient of the axisymmetric mean spray flow on droplet shapes was not dominantly strong.

In summary, the shadow Doppler velocimetry was found an effective measurement tool to clarify the phenomena in spray flows.

Acknowledgement

The authors are grateful to Prof. Taylor at Imperial College, Prof. Maeda at Keio University and their research groups for their advice on developing the present shadow Doppler velocimetry system.

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