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Effect of Disk Edge Profile on Scattering Characteristics of Liquid Droplets Splashed from Spinning Disk

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ABSTRACT

Effects of disk edge profile on scattering characteristics of liquid droplets splashed from a rotating disk edge are experimentally investigated. In the present research, aluminum disks are utilized and purified water is employed for liquid. Scattering phenomena of the droplets are captured by the high-speed digital camera. Distribution of the droplet diameter is evaluated from these images and distributions of horizontal flying velocity component and angle of the droplets are measured by human visual observation of images. Liquid filaments are stretched outward from the stagnant liquid layer on lateral surface of disk edge by centrifugal force. Two main peaks appear in the distribution of the scattered droplet diameter and they are originated from large terminal droplets and small droplets generated from filamentwise breakup. Most of the scattered droplets fly slightly inside of the tangential direction of the disk edge. The water droplets splashed from the disk scatters with regularity compared with ethanol droplets.

Keywords: Scattering Droplet; Spinning Disk; Disk Edge Profile; Visualization

1. Introduction

Recently, development of high technology has been required for formation of thin uniform film in manufacturing process of semiconductor. Spin coating method is widely used for spreading photoresist on the wafer and thickness of the photoresist film attains thinner than 0.5 μm. If the mist of the scattered photoresist reattaches on the liquid film surface in the process, it interferes in the uniform film formation. On the other hand, in rinse process, rinse solution runs down on the wafer printed electric circuits in order to wash away the developing and etching solutions. If the mist of the scattered liquid reattaches on the wafer in the process, it makes water mark on the wafer surface and the particle bridges and damages the electric circuits on the wafer. Many researchers have investigated on filament formation and atomizing of viscous fluids from the rotating disk and air boundary flow over the disk [1-7]. However, the scattering characteristics of the liquid droplets and the reattachment phenomena of the mist on the wafer and effect of disk edge profile have not been clarified yet [8]. Main objective of the present research is to make clear the effect of disk edge profile on the scattering characteristics of the liquid droplets splashed from the rotating disk edge experimentally. Top view images of scattered droplets are captured by a high-speed digital camera and distributions of horizontal flying velocity component and angle of the scattered droplets are measured under the condition of the disk rotating speed $N = 1000$ rpm and liquid flow rate $Q_L = 0.5$ L/min.

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2. Experimental Procedure

Figure 1 illustrates the schematic view of the experimental apparatus in the present research. It is composed of the spin coating device and measurement equipment. These are enclosed with a transparent acrylic box because of the safety. The movements of the entire devices are controlled with a control panel. As the upper part of the wafer surface is opened to atmosphere. The wafer (diameter $2R = 300$ mm, thickness $t_e = 0.78$ mm) is adsorbed to a chuck by a vacuum pump and the rotating speed of the wafer N is less than 4000 rpm. In the present study, aluminum disks (thickness at the edge $t_e = 0.72$, 0.77, 0.78 mm) combined with chuck are utilized instead of the wafer for the sake of safety. As shown in **Figure 2**, the upper corner at the disk edges is treated with a slope

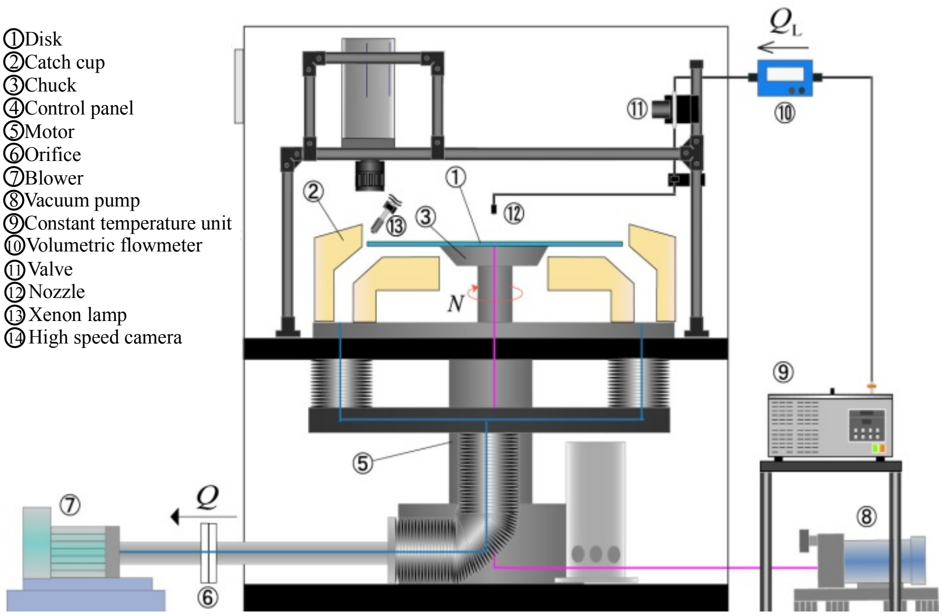


Figure 1. Schematic of the experimental setup.

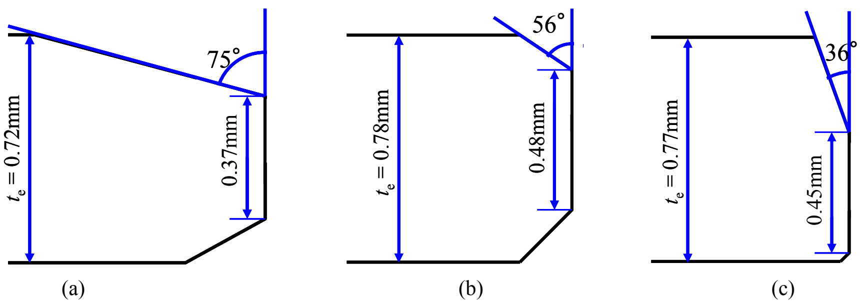


Figure 2. Disk edge profile: (a) Type A; (b) Type B; (c) Type C.

of 75˚, 56˚, 36˚ similar to the standard of the wafer and lateral surface heights of disk edge has slight difference because of manufacturing precision. Purified water filtered with microfiltration membrane is employed for liquid or rinse solution, as it is frequently used in the rinse process and safety of handling. Flow rate of water is controlled by valve and water is discharged on the disk center through the nozzle (diameter 3.9 mm) simply, though the wafer is washed in a variety of ways during the rinse process. After water is fully fed over the disk, the disk is spun up to rotating speed N = 1000 rpm (angular velocity ω = 105 rad/s) and the speed is kept.

The behavior of the liquid droplets splashed from the disk edge is captured by high-speed digital camera (PHOTORON FASTCAM SA-X) above the disk as shown in **Figure 1**. Experimental conditions are summarized in **Table 1**. The photographing area is confined between the disk edge and the catch cup and illuminated by the xenon lamp. Downward air flow is generated between the disk edge and the catch cup by the blower.

From the captured images for one rotation of the disk, droplet diameter and droplet location are obtained by human visual observation. The horizontal flying velocity and angle of the liquid droplet are obtained at the midpoint of flying path for inter-frame spacing. The horizontal flying angle is defined as the angle formed by the horizontal droplet flying direction and the tangential direction of the circle centered on the disk center through the midpoint. The droplets which are not related in a pair of the images are deleted from the results.

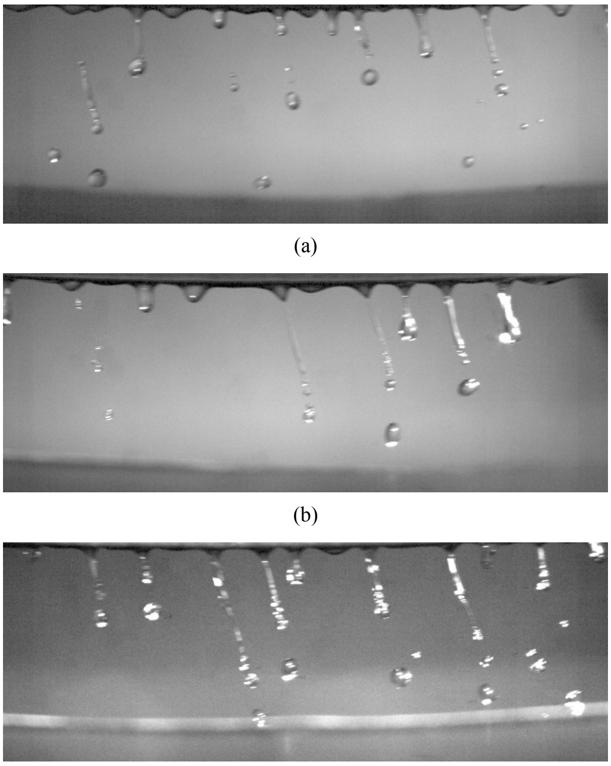
Measurement uncertainty of the present experiment is mainly caused by the error of the evaluation of the droplet center. As the other errors must be negligibly small, uncertainty of the horizontal flying velocity of the droplet is roughly estimated U_u = 0.79 m/s. Uncertainty of the horizontal flying angle of the droplet U_α increases from 1.4˚ to 1.8˚ with a decreasing of the droplet velocity in the experimental range.

3. Experimental Results and Discussion

Figure 3 shows the captured images of liquid filaments

Table 1. Experimental condition.

Rotating speed N [rpm]	1000
Liquid	Water
Liquid flow rate Q_L [L/min]	0.5
Exhaust air flow rate Q_{ex} [m^3/min]	2
Inter-frame spacing [μs]	100
Shutter speed [μs]	10
Resolution [μm/pixel]	29



(a)

(b)

(c)

Figure 3. Captured images of filaments and droplets: (a) Type A; (b) Type B; (c) Type C.

and droplets splashed from the rotating disk edge for disk type A, B and C. The disk is rotating upper side of the image from right to left. Liquid flowing down on the disk is stagnant on the lateral surface of the disk edge and stagnant thin liquid layer is formed. A lot of liquid filaments are stretched outward from the liquid layer by the centrifugal force. It is well known that the shape of the filament is an involute curve if the aerodynamic force does not act on the liquid filament. It is obvious that all of the filaments are slightly inclined in the counter-rotating direction. The liquid filaments are decelerated by the aerodynamic force. All of **Figures 3(a)-(c)** are classified into quasi-dropwise breakup. Relatively large droplets are observed near the filament tip and residual filament breaks into some small droplets (filamentwise breakup). The liquid filament of **Figure 3(a)** is slimmer and shorter than that of **Figures 3(b)** and **(c)** and its terminal droplets fly away near the disk edge.

Figure 4 shows distribution of the droplet diameter and **Table 2** summarizes statistics of the droplet diameter. In **Figure 4**, each distribution is normalized by number of the droplets. Two main peaks of the droplet diameter appear for the thick and thin disks. It is presumed that the small peaks around d = 600 μm correspond to the terminal droplets, as shown in **Figure 3**. On the other hand, the peak around d = 280 μm is originated from the small droplets generated from the filamentwise breakup. In the following results, the measured droplets are readily divided into two groups of the droplet diameter, d < 500 μm, and d > 500 μm.

Figure 5 represents the distributions of the horizontal flying velocity and angle of the small size droplets. If it is assumed that a sphere linearly flies away in tangential direction from the circle of radius r_b, the droplet flying angle α at radius r is geometrically calculated by Equation (1).

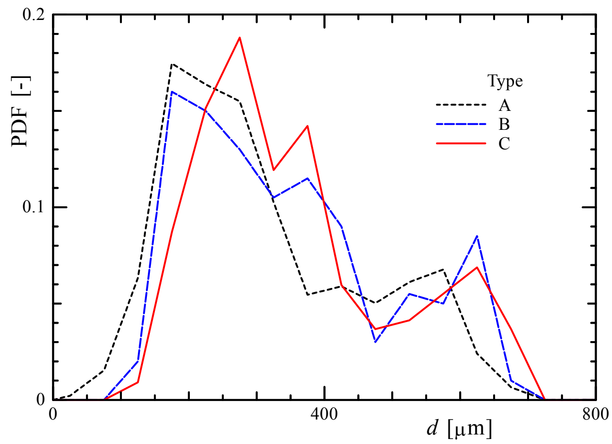


Figure 4. Distribution of droplet diameter.

Table 2. Statistics of droplet diameter: (a) Small size droplet (d < 500 μm); (b) Large size droplet (d > 500 μm).

(a)

Type	A	B	C
Number of droplets	383	154	165
Mean diameter d_m [μm]	265	288	306
Std.dev. σ_d [μm]	100	92	81

(b)

Type	A	B	C
Number of droplets	73	40	44
Mean diameter d_m [μm]	566	593	600
Std.dev. σ_d [μm]	40	46	51

$$\alpha = \cos^{-1}\frac{r_b}{r} \quad (1)$$

In **Figure 5**, $\Delta\alpha$ is deviation angle defined by Equation (2).

$$\Delta\alpha = \alpha - \alpha_R,\ \alpha_R = \cos^{-1}\frac{R}{r} \quad (2)$$

Red line in **Figure 5** is a fitting curve obtained by least square method. Most of the plotted data points take slightly negative value. It means that the droplets fly somewhat inner side of the tangential direction from the disk edge. It is caused that the liquid filaments are stretched from the stagnant liquid layer formed outer side

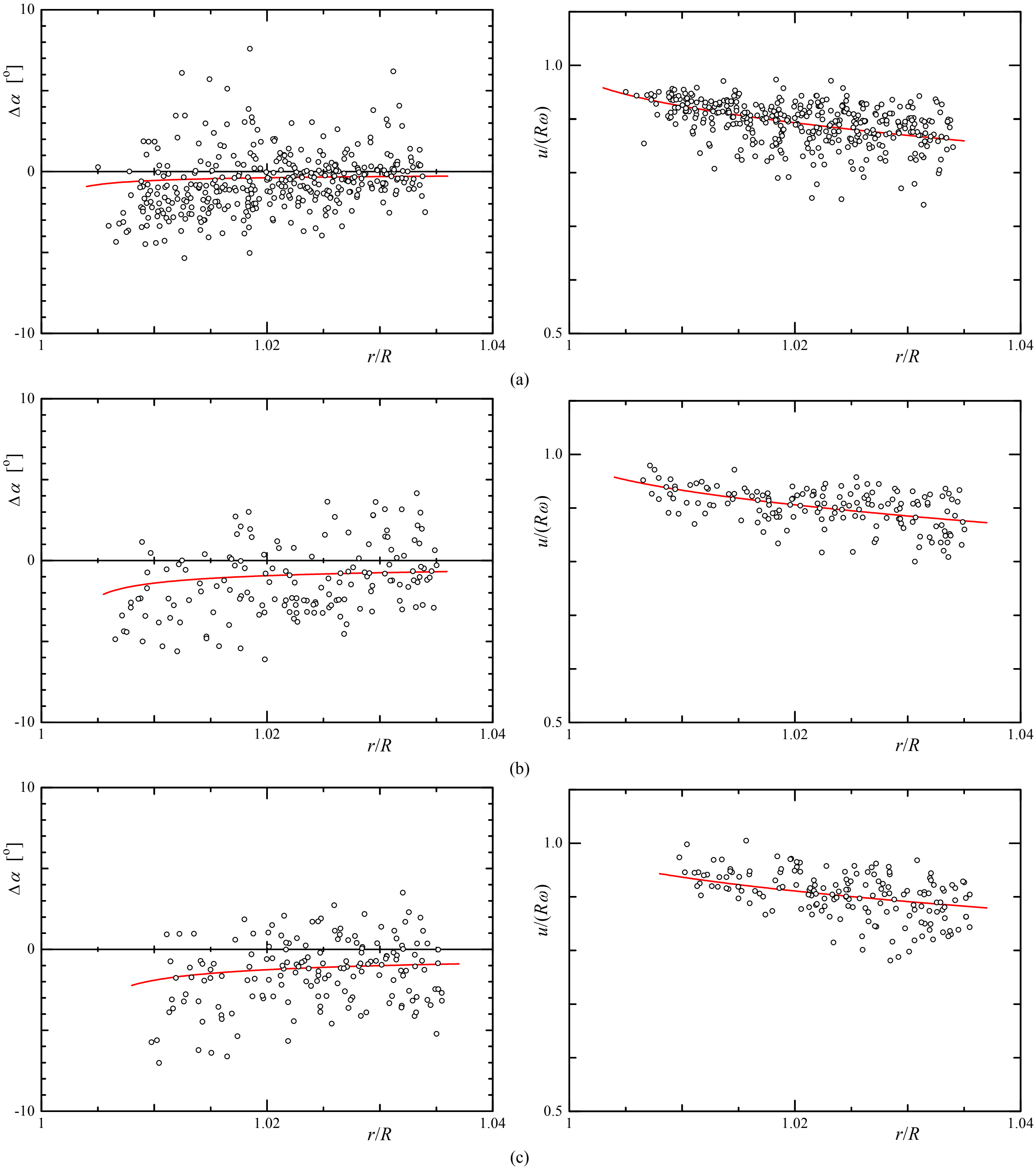


Figure 5. Horizontal flying angle and velocity of small size droplet (d < 500 μm): (a) Type A (left: angle, right: velocity); (b) Type B (left: angle, right: velocity); (c) Type C (left: angle, right: velocity).

of lateral disk edge as shown in **Figure 3**. It is clear that this deviation of type B and C is remarkable as the liquid filament of them is large and the stagnant layer of them is thick.

Furthermore, if it is assumed that the droplet flies horizontally and Allen's experimental Formula [9]

$$C_{\mathrm{D}} = 10 Re^{-1/2}, \quad Re = \frac{ud}{\nu_{\mathrm{air}}} \tag{3}$$

can apply on the drag acting on the droplet, the droplet flying velocity is estimated by Equation (4) derived from an equation of motion of a rigid sphere in a stationary air.

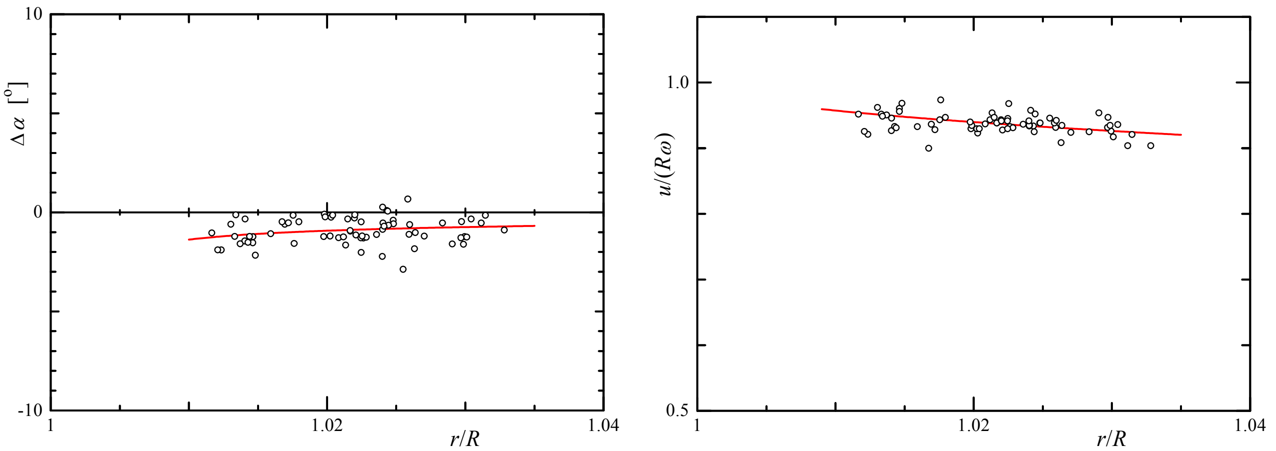
$$u = u_{\mathrm{b}} \left(1 - \frac{15}{4d} \frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{L}}} Re_{\mathrm{b}}^{-1/2} \sqrt{r^2 - r_{\mathrm{b}}^2} \right)^2 \tag{4}$$

where u_{b} is the droplet flying velocity at the radius r_{b}. As shown in **Figure 5**, the droplets are monotonically decelerated in the radius direction by the drag force. For type A, the deceleration of the droplets and the deviation of the data points from the fitting curve are remarkable. It is clear from **Figure 5** that the smaller size droplet of type. A results in slower horizontal velocity as recognized from Equation (4).

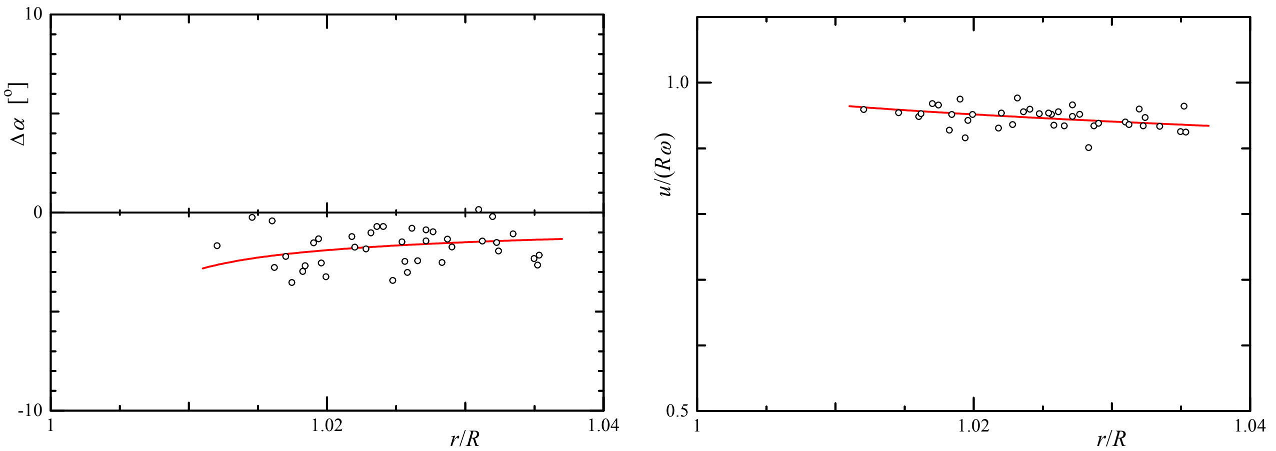
The distributions of the horizontal flying velocity and angle of the large size droplets are shown in **Figure 6**. The droplet flying velocity and angle are very close to the fitting curve, almost within order of the measurement uncertainty. The fitting curve of angle in **Figure 6** is almost similar to that in **Figure 5**. On the other hand, the deceleration of large size droplet is smaller than that of small size droplet as recognized from Equation (4).

4. Conclusions

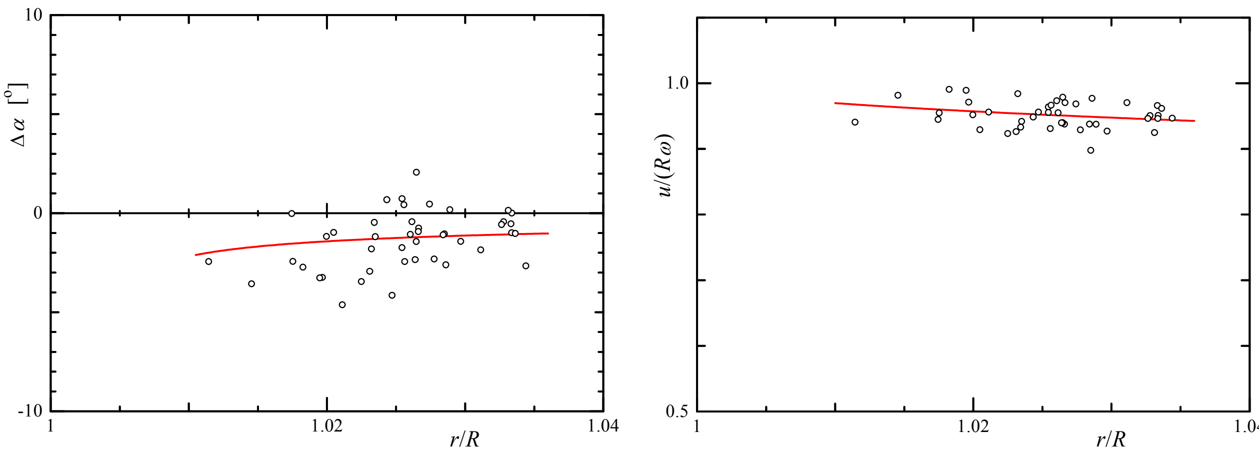
The effects of disk edge profile on scattering characteristics of the liquid droplets splashed from the rotating disk edge have been investigated experimentally. The scattering phenomena of the droplets were captured by the high-speed digital camera. The distribution of the droplet diameter was evaluated from these images and the distributions of the horizontal flying velocity component and angle of the droplets were measured. Main results obtained are summarized as follows.



(a)



(b)



(c)

Figure 6. Horizontal flying angle and velocity of large size droplet (*d* > 500 μm): (a) Type A (left: angle, right: velocity); (b) Type B (left: angle, right: velocity); (c) Type C (left: angle, right: velocity).

The liquid filaments are stretched outward from the stagnant liquid layer on the lateral surface of the disk by the centrifugal force and inclined toward counter-rotating direction.

Two main peaks appear in the distribution of the scattered droplet diameter and they are originated from the large terminal droplets and the small droplets generated from the filamentwise breakup.

Most of the scattered droplets fly slightly inside of the tangential direction on the disk edge because the liquid filaments are stretched outward from the stagnant liquid layer on the lateral surface of the disk.

The droplets splashed from the thin disk edge scatter rather wider than that from the thick one because the liquid filament is slim and the small droplets are generated. On the other hand, there is not apparent discrepancy for scattering of large terminal droplets.

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