Atomization of Liquid Issued from an Ultra High-speed Rotary Bell

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Abstract

The purpose of this study is to investigate how the flow pattern of a liquid film formed on an ultra high-speed rotary bell, and its breakup at the outer edge of the bell, affect the liquid atomization. We observed the breakup pattern produced at the edge of a rotary bell and studied whether or not the characteristics of the atomization produced by the rotary bell used in this study, agree with the results of previous studies. We categorized the flow pattern on the surface of the rotary bell, which varied with the rotational speed and the liquid flow rate, and categorized the liquid breakup patterns at the edge. At lower rotational speeds, it was confirmed that the liquid on the rotary bell's surface was a smooth film, and the liquid breakup patterns at the outer edge were a pseudo-dropwise breakup in which large droplets were formed, in addition to Rayleigh breakup resulting from the detachment of several long ligaments. At higher rotational speeds, it was confirmed that fine ligamentwise breakup wherein the dropsize distribution can be relatively narrow took place as a result that lots of small waves were generated which in turn developed into serrated waves whose tip-end portions became saw-tooth shapes in the liquid flow, the breakup pattern at that time was such that lots of fine ligaments were elongated and subsequently split into fine droplets. We confirmed promotion of atomization, while we considered that the liquid film as serrated wave was largely attributable to be issued from the edge of rotary bell.

Introduction

The atomization of liquid by centrifugal force [1], [2] is not only suitable for highly viscous liquid but is also able to generate liquid droplets with relatively uniform drop sizes. For this reason, it has been widely used for spray painting, spray drying, etc. With a focus on atomization using the ultra high-speed rotary bell, the purpose of this study is to investigate how the shape of its rotary bell and the flow characteristics of the liquid affect the atomization. In the present paper, we have investigated how the flow patterns of a liquid film formed on the surface of rotary bell affect the breakup patterns of atomization at the outer edge, and studied whether or not the characteristics of the atomization produced by the rotary bell used in this study agree with the results of previous studies.

Experimental Procedures

Figure 1 shows the experimental apparatus. Tap water was used, where the pressurized air from the compressor is supplied to tank and air motor (with pneumatic bearing). The motor equipped with a rotary bell is rotated at high speed, and the liquid is supplied to the inner surface of the rotary bell from the supply ports in the bell's center. We observed the breakup patterns from the outer edge of the rotary bell and the flow patterns on the surface via transmitted and reflected light, respectively, using the nano-pulse light, while taking photographs using the digital camera. The flow patterns formed on the surface of the rotary bell were categorized according to the rotational speed and the liquid flow rate, the breakup patterns at the outer edge of the rotary bell were also categorized, and a study was conducted in comparison with the results of study concerning a flat disk [1] and the other results of a flat disk having a small diameter [3].

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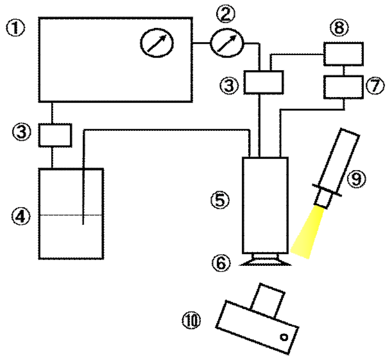
Figure 2 shows the measurement method of the liquid film velocity on the bell's surface. In this method, a pair of nano-pulse lights were used, photographs were taken by emitting a light of a different color from that of the nano-pulse lights when the rotary bell rotated to an angle of 3 degrees after a light was emitted from the other nano-pulse light via a pulse generator, then the velocity was determined by measuring the moving distance of the liquid film in the images of photographs. The measurement location was situated at a point 20 mm away in a radial direction from the bell's center. The delay time ranges from ΔT=500 to 16.67 μs respectively, which corresponds to the rotational speed N=1,000 to 30,000 rpm.

The rotary bell used in this study has a diameter of 50 mm, which has 60 liquid supply ports on circumference of 21 mm in diameter. Although a rotary bell which is provided with grooves on the outer peripheral edge was mainly used, another rotary bell with no grooves was also used for comparison. The rotational speed N, which may affect the liquid atomization such as breakup patterns at the outer edge and flow patterns on the surface of the rotary bell, was set within the range 1,000 to 50,000 rpm. The liquid flow rate Q was varied from 50 to 300 mL/min.



① Compressor
② Pressure gauge
③ Regulator
④ Tank
⑤ Air motor
⑥ Rotary bell
⑦ Tachometer
⑧ PID controller
⑨ Nano-pulse light
⑩ Digital camera

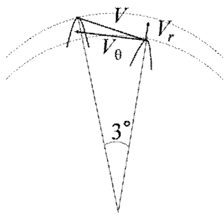


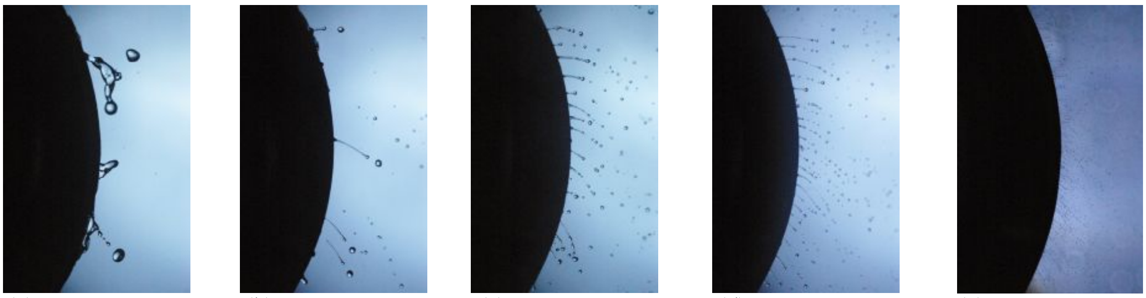
Figure 2 Measurement method of the liquid film velocity

Figure 1 Experimental setup

Results and Discussion

1. Breakup Patterns at the Rotary Bell Edge

Figure 3 shows the breakup patterns at the outer peripheral edge of the rotary bell, which vary with the rotational speed N, when the flow rate Q is fixed to 200 mL/min. Note that the report from Suzuki et al. concerning ultra high-speed rotary disks [3] was used as a reference to classify these breakup patterns. At lower rotational speeds, we observed the pseudo-dropwise breakup, in which large liquid droplets were formed at the outer edge of the rotary bell as shown in Fig. 3(a) and the Rayleigh breakup resulting from the long ligaments from several locations as shown in Fig. 3(b). At higher rotational speeds, we observed the dropwise breakup, in which relatively large liquid droplets were formed directly from the outer edge of the rotary bell as shown in Fig. 3(c), and when increasing the rotational speeds, we observed the ligamentwise breakup, as shown in Fig. 3(d), wherein ligaments were elongated at almost uniform pitch from the outer edge and subsequently split into fine droplets. At ultra high rotational speeds (N = 20,000 rpm or higher), we observed, as shown in Fig. 3 (e), fine ligamentwise breakup, in which many fine

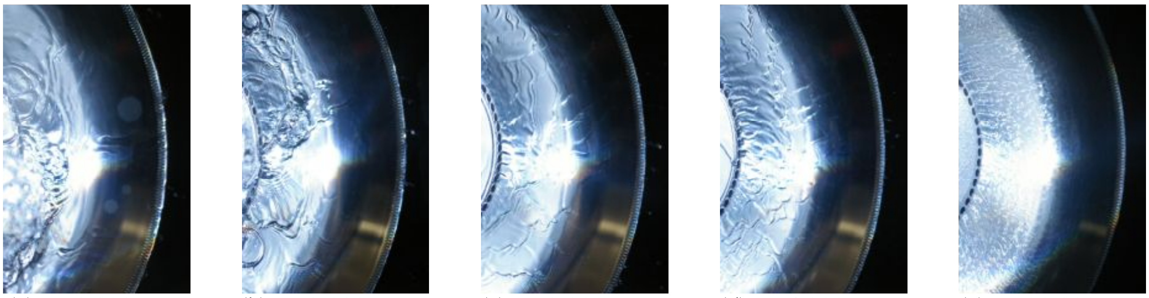


(a) N=1,000 rpm (b) N=2,000 rpm (c) N=3,000 rpm (d) N=4,000 rpm (e) N=20,000 rpm

Figure 3 Typical breakup patterns at rotary bell edge (Q=200 mL/min) ligaments were elongated from the outer edge and split into fine droplets, wherein the variations in their drop sizes were small.

2. Flow Patterns on the Rotary Bell Surface

Figure 4 shows how flow patterns on the surface of the rotary bell vary with the rotational speed *N*, when the flow rate was fixed to 200 mL/min. Again, the report from Suzuki et al. [3] was used here as reference for classification of the flow patterns. Observing lower rotational speeds (Figs. 4 (a) and (b)), we can see that the liquid film changes to be smooth as it moves away from the center, even though the liquid film near the center is disturbed. In this case, both the pseudo-dropwise breakup and Rayleigh breakup (Figs. 3(a) and (b)) were observed at the outer edge of the rotary bell. At higher rotational speeds, we observed the roll wave as shown in Fig. 4(d). When the rotational speeds were increased further, we confirmed that many waves were generated on the surface and their tip-end portions became saw-tooth shapes (serrated waves), as shown in Fig. 4(e). When such serrated waves were generated, the breakup patterns at the outer edge were the ligamentwise breakup and fine ligamentwise breakup (Fig. 3(e)), and the atomization was excellent.



(a) N=1,000 rpm (b) N=2,000 rpm (c) N=3,000 rpm (d) N=4,000 rpm (e) N=20,000 rpm

Figure 4 Typical liquid flow patterns on rotary bell surface (Q=200 mL/min)

3. Classification of Breakup Patterns Formed at the Rotary Bell Edge

Figure 5 shows the variations of breakup patterns with the liquid flow rate and rotational speeds, where the solid line shown in the figure refers to the following empirical equation regarding the critical flow rate Q_1 of the dropwise breakup of a flat disk [1]:

$$Q_1 = 60.3\left(\frac{D}{N}\right)^{2/3}\left(\frac{\sigma_L}{\rho_L}\right)\Bigg/\left[1+10\left\{\frac{\mu_L}{(\rho_L\sigma_L D)^{0.5}}\right\}^{1/3}\right] \tag{1}$$

This equation means that a breakup pattern will become a dropwise breakup pattern if the flow rate is below this flow rate. On the other hand, the dashed line indicates the following equation, which gives a minimum pitch of the ligaments:

$$Q_2 = 172.4\left(\frac{D}{N}\right)^{2/3}\left(\frac{\sigma_L}{\rho_L}\right)\Bigg/\left[1+10\left\{\frac{\mu_L}{(\rho_L\sigma_L D)^{0.5}}\right\}^{1/3}\right] \tag{2}$$

In this study, we observed the pseudo-dropwise breakup and dropwise breakup when the flow rate was below the critical flow rate of dropwise breakup Q_1. We also observed the fine ligamentwise breakup, in addition to ligamentwise breakup, when the flow rate was above the critical flow rate of dropwise breakup, i.e. in the ligamentwise breakup area. In areas where the liquid flow rate was high (Q=200 mL/min or higher), however, the dropwise breakup was also found at lower rotational speeds. Furthermore, our investigation revealed that no filmwise breakup occurred in the rotary bell used for this study, and our experimental results did not correspond to the experimental results of flat disks [1]. This finding is considered to be attributable to the effects of the shape of the rotary bell and the grooves at the outer edge.

4. Classification of the Flow Patterns of Liquid Film

Figure 6 shows the variations of the flow patterns of the liquid film on the rotary bell's surface with liquid flow rate and rotational speed. In this study, we mainly observed the smooth film in the lower rotational speed, the roll wave in the medium rotational speed, and the serrated wave in the high rotational speed. In other words, this means that the flow patterns are not affected by the flow rate, but significantly by the rotational speed. Also, the shaded area in Fig. 6 refers to that on which the fine ligamentwise breakup area shown in Fig. 5 was superimposed, from which we can see that the area virtually corresponds with that where the serrated wave is generated on the bell's surface.

When the liquid film is thinned and the serrated waves are formed due to higher rotational speeds, the flow rate in each groove at the outer edge is relatively uniform, thus the fine ligamentwise breakup in which the drop size distribution is expected to be well.

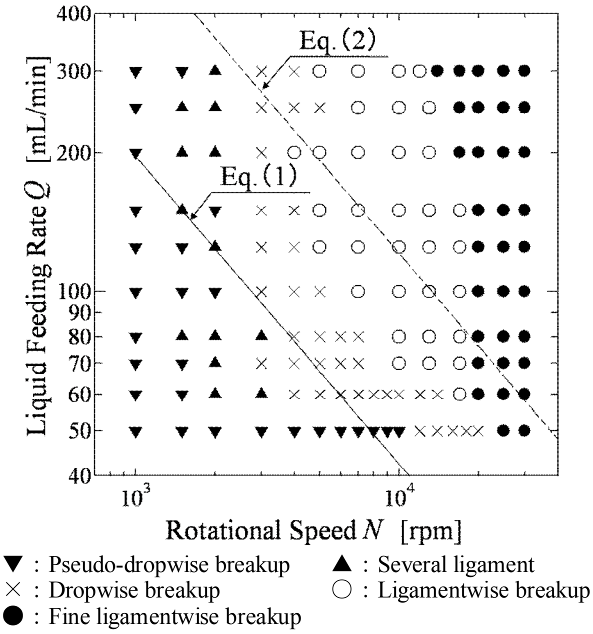


Figure 5 The variations of breakup patterns with the liquid flow rate and rotational speed

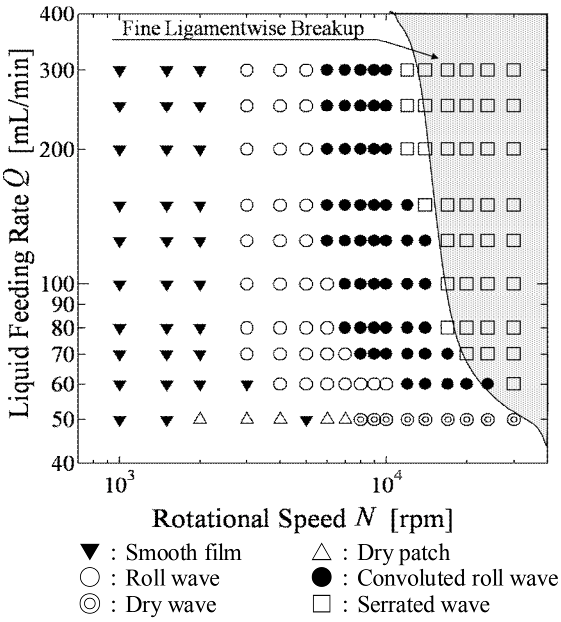


Figure 6 The variations of the flow patterns of the liquid film with liquid flow rate and rotational speed

5. Liquid Film Velocity

In the previous sections 3 and 4, we have shown that the flow patterns of liquid film on the bell's surface have a significant effect on the breakup patterns. Although, for the liquid film's flow patterns, it is important to analyze the film thickness and its variation, the radial/circumferential velocity and its distribution, we measured the liquid film velocity and compared the experimental results with the theoretical ones. The surface velocity of the liquid film in the radial direction, V_r at r is theoretically obtained from the following equation [4];

$$V_r = \left(\frac{9\omega^2 Q^2 \rho_L \sin\theta}{32\pi^2 \mu_L r} \right)^{1/3} \qquad (3)$$

where ω is the angular velocity (=$2\pi N/60$) [rad/s], ρ_L is the density [kg/m^3], μ_L is the viscosity [Pa·s], and θ is the tangential angle of the bell's surface to the revolving shaft of the air motor.

Figure 7 shows the variation of radial velocity of the liquid film at r=20 mm with rotational speed. The dashed lines shown in the figure refer to the theoretical values which were obtained from eq. (3) for each flow rates (Q =50, 150 and 300 mL/min), and ●, ■ and ▲ show the measured values. It can be seen from this figure for each flow rate that as the rotational speed increases, both the theoretical and measured values of the radial velocity increase, although the measured values are larger than the theoretical ones. The difference between the measured values and the theoretical ones may result from the fact that the rotary bell has 60 liquid supply ports where the liquid is fed with a finite radial velocity and then forms a continuous liquid film, hence causing slippage to occur between the supplied liquid and the bell's surface, and there exists a portion where the angle of the bell's surface θ will suddenly vary after the measured point of liquid film velocity.

Figure 8 shows the variation of liquid film velocity with the rotational speed. In this case the liquid film velocity V shown as the dashed line is derived from the equation below;

$$V = \sqrt{V_\theta^{\,2} + V_r^{\,2}} \tag{4}$$

where V_r is the radial velocity given by eq. (3), and $V_\theta(=r\omega)$ is a circumferential velocity with no slippage between the liquid film and the bell's surface. As the circumferential velocity V_θ is much larger than the radial velocity V_r, the flow rate has little or no effect. Although points such as ●, ■ and ▲ are indicative of each measured value when each of the flow rates are Q = 50, 150 and 300 mL/min, it is clear that the liquid film velocity slightly increases as the flow rate increases. On the contrary to the radial velocity case shown in Fig.7, it is found that the measured values of liquid film velocity become smaller than their theoretical ones. It may result from the slippage between the liquid film and the bell's surface in the circumferential direction, some force in a direction opposing that of rotation acts on the liquid film which flows in a radial direction due to Coriolis force, and other factors.

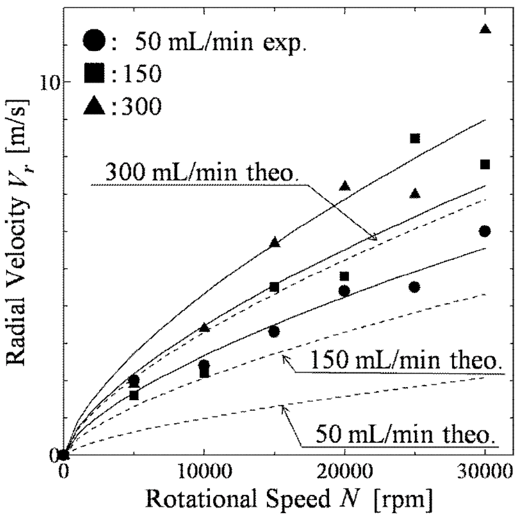


Figure 7 The variation of radial liquid film velocity with rotational speed

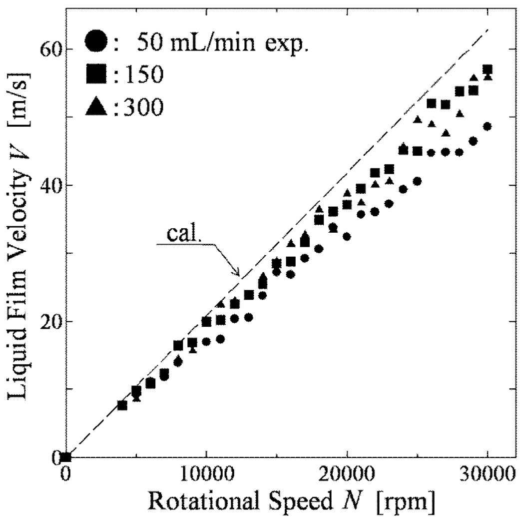


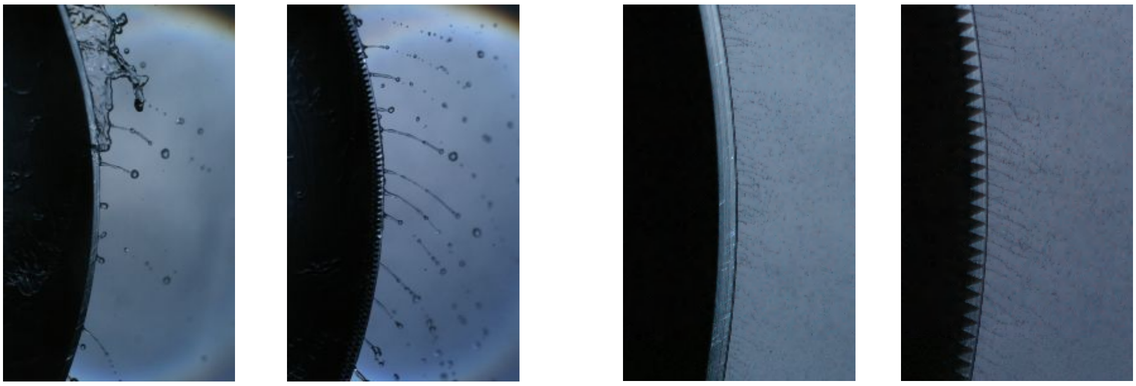
Figure 8 The variation of liquid film velocity with rotational speed

6. Effects of Grooves Located at the Outer Edge on Atomization

Figure 9 shows the comparison results between the rotary bells with and without grooves at the outer edge with regard to each of their breakup patterns; based on conditions where the flow rate is Q=300 mL/min, and the rotational speed is N = 3,000 or 40,000 rpm.

At lower rotational speeds, it can be seen from the rotary bell without grooves (Fig. 9(1) (a)) that a filmwise breakup occurs partially, and several ligament are produced from various portions. By contrast, it can be seen from the rotary bell with grooves (Fig. 9(1) (b)) that no liquid film is formed, and several ligaments are produced from the grooves at the outer edge and broken up. This is likely to be the reason why the breakup patterns at the outer edge differ, as shown in these figures, despite having the same operating conditions (the rotational speed and liquid flow rate), due to effects whereby the grooves have an effect to divide the liquid film at the outer edge.

At higher rotational speeds, it can be seen from the rotary bells without grooves (Fig. 9(2) (a)) and with grooves (Fig. 9(2) (b)) that there is a fine ligamentwise breakup in each bell. However, despite the fact that a smaller diameter and shorter length of ligaments are found in the rotary bell without grooves, the pitch of the ligaments is irregular and the dropsize distribution can be wider. In contrast, it can be seen from the rotary bell with grooves that the diameter of the ligaments is larger than that found in the rotary bell without grooves, though the ligaments are more elongated. We can also recognize that the number of ligaments at the edge almost agrees with that of the grooves at the outer edge (440). It was observed that the liquid droplets generated in this case have smaller drop sizes and more narrow dropsize distribution than those generated in the rotary bell without grooves.



(a) With no groove (b) With groove (a) With no groove (b) With groove
(1) *N*=3,000 rpm (2) *N*=40,000 rpm

Figure 9 Comparison of breakup phenomena (*Q*=300 mL/min)

Conclusions

In the present paper, we investigated how the flow pattern of a liquid film formed on an ultra high-speed rotary bell, and its breakup at the outer edge of the bell, affect the liquid atomization. The results obtained are as follows:

1) Flow patterns of a liquid film on the rotary bell's surface were categorized according to the rotational speed and the liquid flow rate.
2) We identified the fact that flow patterns of a liquid film on the bell's surface affected the breakup patterns at bell's the outer edge.
3) We categorized the breakup patterns at the bell's outer edge into dropwise, ligamentwise fine ligamentwise breakup.
4) In case that the flow pattern of a liquid film on the surface is a serrated wave, we confirmed that the breakup pattern at the outer edge became fine ligamentwise breakup and the atomization was excellent.
5) We confirmed that the measured radial velocity of the liquid film on the rotary bell's surface became larger than the calculated result due to the effect of the shape of the bell.
6) It was found that the measured value of liquid film velocity on the bell's surface is smaller than the calculated value under the influence of slippage in a circumferential direction of the liquid film.
7) It was confirmed that the grooves at the outer edge have an effect to divide the liquid film at the outer edge, and produce small droplets wherein the dropsize distribution can be narrow.

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