Liquid Atomization of a Radial Liquid Sheet Due to Transition to Turbulence*

Tatsuro WAKIMOTO** and Tsuneo AZUMA**

In this paper, the mechanisms of breakup and drop formation of a radially thinning liquid sheet, which are attributed directly to the transition from laminar to turbulent flow, are described. A radial liquid film flow is generated by water discharge from one end of a cylindrical nozzle through a small gap present between the end of the nozzle and the flat surface of a disk. The liquid film spreads radially outward on the disk as a sheet, flowing from the edge of the disk into the air. Sudden laminar-turbulent transition occurs in the liquid sheet when the Reynolds number exceeds a critical value, resulting in both perforation and disintegration of the sheet under an extremely high Reynolds number. The breakup process through perforation, ligament formation and drop formation is observed both by zoom-in photography using a single pulse strobe and a steel camera and high-speed photography using a multipulse laser and a drum streak camera. These photographs clearly show that droplets a few tens of micrometers in size are produced from the liquid sheet. Flow conditions for the occurrence of atomization induced by the transition are also presented.

Key Words: Transition, Free Surface Flow, Atomization, Boundary Layer, Radial Flow, High-Speed Photography

1. Introduction

Liquid atomization is applied in various industrial applications including coating, spray drying and spraying of agricultural chemicals, and various methods of liquid atomization have been developed in accordance with the objectives of their use. Clarification of the mechanism of the liquid atomization phenomenon is essential for improving the performance of spray nozzles and atomization devices. Accordingly, a large number of studies regarding the instability, disintegration and drop formation of liquid jet flows and liquid sheets have been performed. However, because of the complexity of the phenomenon, the mechanism has not yet been completely clarified.

With respect to the instability, i.e., the cause of

the atomization of a liquid sheet, the following studies have been reported: analyses of the sinuous wave motion of a liquid film flow from spray-fan nozzles and observation of the unstable wave formation and atomization process conducted by Squire⁽¹⁾, Hagerty and Shea⁽²⁾, Fraser et al.⁽³⁾, and Dombrowski and Johns⁽⁴⁾; analyses of the Kelvin-Helmholtz-type wave of a two-dimensional liquid film accompanied by parallel high-speed air flow performed by Arai and Hashimoto⁽⁵⁾, and Rangel and Sirignano⁽⁶⁾; observation of the unstable wave formation and atomization process conducted by Arai and Hashimoto⁽⁷⁾, Mansour and Chigier⁽⁸⁾, and Lozano et al.⁽⁹⁾ Recently, research on the liquid atomization of a radial liquid sheet generated from the collision of a liquid jet flow with a disk has been conducted; Spielbauer and Aidun⁽¹⁰⁾ clarified the perforation phenomenon which occurs as a result of the formation of a thin film due to the expansion of a liquid film and superimposition of sinuous wave motions, McCreery and Stoots⁽¹¹⁾ clarified the drop formation phenomenon on the basis of the stability theory proposed by Dombrowski and Johns. These studies concern cases in which the velocity distribution inside the liquid film can be neglected.

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** Department of Mechanical Engineering, Faculty of Engineering, Osaka City University, 3-3-138 Sugimoto, Sumiyoshiku, Osaka 558-8585, Japan. E-mail: wakimoto@mech.eng.osaka-cu.ac.jp

The authors previously clarified that laminar-turbulent transition due to the laminar boundary-layer velocity distribution occurs in a liquid film flowing radially on a disk⁽¹²⁾⁻⁽¹⁶⁾. In addition, using disks with fairly small diameters, we reported that laminar-turbulent transition due to inflection-type velocity distribution inside the liquid film occurs in a radial liquid sheet generated by the leaving of the liquid film, which was developed from the laminar boundary-layer velocity distribution, from the edge of the disk⁽¹⁷⁾⁻⁽¹⁹⁾.

When laminar-turbulent transition is induced by liquid film flow, the liquid film is dominated by fine granular waves (vortex, eddy current). This research was initiated with the aim of inducing liquid atomization, by making use of the strong vortex motion induced by the laminar-turbulent transition in the radial liquid sheet. To our knowledge, no reports have described the atomization of liquid films, from the viewpoint of clarification of the laminar-turbulent transition.

In this paper, we clarify the process of laminar-turbulent transition, perforation in liquid films due to the laminar-turbulent transition and atomization process by means of magnified photography and high-speed continuous photography. In addition, we describe the conditions under which atomization occurs by generation of droplets with a particle size of 20 - 30 μm due to the laminar-turbulent transition. Quantification of the perforation phenomenon in liquid films and the effects of surface tension on the size and flying speed of generated drops and on atomization will be reported in the future.

2. Experimental Apparatus

Figure 1 shows a diagram of the experimental apparatus used in the atomization experiments. A cylindrical thin gap is formed between the tip of a cylindrical nozzle and a disk placed normal to the nozzle. When pressured water flows out from the nozzle through this gap, a radial liquid film flow is formed on the disk. In the radial liquid film flow, a

Fig. 1 Experimental apparatus

laminar boundary layer develops inside the liquid film; after the boundary layer reaches the liquid surface, the liquid film flows with the velocity distribution of a laminar boundary layer. In the present study, such a liquid film in which a boundary layer was developed flows from the edge of the disk into the air so that a radial liquid sheet is formed. In the experiments, a nozzle with an inner diameter of 25 mm and 5 disks with diameters of 40, 60, 70, 80 and 100 mm were used. The inner wall of the nozzle forms a sharp right angle (without roundness) with the nozzle rim and the sides of the disks are also at right angles to the top surfaces to facilitate easy water removal from them. The top and lateral surfaces of the disks are fabricated to have 2 μm or less of surface roughness. The following flow conditions were evaluated to determine the occurrence of atomization of a radial liquid sheet: the gap between the nozzle and the disk was varied from 0.1 mm to 0.7 mm at intervals of 0.05 mm. In addition, when a 60-mm-diameter disk and 0.15 mm gap were used, the laminar-turbulent transition and processes of perforation, breakup and atomization were observed in detail.

The laminar-turbulent transition as well as the perforation, breakup and atomization processes were photographed by a 35 mm steel camera using a strobe with three flash durations: 30, 2 and 0.2 μs . To observe the time-course change in the features of the liquid film, the liquid film flow was also photographed by high-speed continuous photography using a multipulse laser (Nd-YAG, output: 10 mJ, flash duration: 0.2 μs , flash interval: 41.7 μs) as a light source and a drum streak camera (MODEL-351, CORDIN Co., Ltd.).

Tap water was used as a sample liquid. To obtain a stagnant pressure at the center of a disk, the static pressure inside the pipe connected to the nozzle 650 mm upstream of the nozzle edge was measured using a pressure transducer. The maximum stagnant pressure achievable with this experimental apparatus was 800 kPa. The flow rate was obtained by collecting the detached liquid films and drops using a casing and by measuring their weight using a platform machine.

Experiments were mainly performed using stationary disks. However, in some experiments, a disk which was rotating at 125 rps was used to examine the effects of disk rotation on the perforation and breakup of liquid films.

The results of the above experiments showed that, when laminar-turbulent transition occurred on a disk prior to the leaving of a liquid film from the disk edge into the air, good atomization could not be achieved. Therefore, to obtain the limit flow conditions with which a laminar-turbulent transition occurs

Table 1 Flow condition

Fig. No.	D mm	H mm	D_d mm	P kPa	Q $\times 10^3$ m ³ /s	T °C	Re_0 $\times 10^{-3}$	r_e^*	r_t^*	U_e m/s	h_e μm	Re_e	We_e
2-a	25	0.15	60	27	0.069	18	38	0.51	—	4.9	121.7	564	40
2-b	25	0.15	60	216	0.166	16	92	0.42	0.55	17.5	81.9	1270	340
2-c	25	0.15	60	339	0.204	17	119	0.39	0.48	23.3	75.7	1620	559
2-d	25	0.15	60	409	0.255	16	136	0.35	0.45	27.4	80.4	1970	821
2-e	25	0.15	60	477	0.279	18	155	0.33	0.42	30.3	79.4	2270	1000
2-f	25	0.15	60	734	0.322	17	182	0.32	0.38	38.0	73.2	2580	1440
3-a	25	0.15	60	395	0.234	30	178	0.33	0.39	27.7	72.9	2500	784
3-b	25	0.15	60	685	0.325	30	241	0.29	0.33	37.1	71.9	3040	1380
4	25	0.15	60	697	0.332	12	163	0.33	0.41	36.9	77.8	2360	1430
5	25	0.27	60	732	0.354	20	204	0.30	0.35	38.3	77.0	2760	1550
7	25	0.25	80	788	0.467	30	306	0.31	0.28	39.8	74.7	3680	1660
8	25	0.3	70	433	0.431	23	213	0.27	0.34	29.5	99.7	2710	1190

at the disk edge, we investigated the position of the transition-radius of the liquid flow on a disk, for cases when the gap between the nozzle and the disk was between 0.1 mm and 0.7 mm.

3. Experimental Results and Discussion

3.1 Flow conditions

The authors previously clarified that the flow characteristics of a radial liquid film formed on a disk could be arranged by the discharge Reynolds number Re_0 defined by Eq. (1) below⁽¹²⁾⁻⁽¹⁴⁾.

$$Re_0 = \frac{Q}{\sqrt{CDH}\nu} \quad (1)$$

Here, Q is the volume flow rate, C is the discharge coefficient of the gap, D is the inner diameter of the nozzle, H is the distance between the nozzle and the disk (gap distance) and ν is the kinetic viscosity. The discharge coefficient C is experimentally obtained by

$$C = \frac{Q}{\pi DH \sqrt{\frac{\rho}{2P}}} \quad (2)$$

where ρ is the density of water and P is the stagnant pressure at the center of a disk. In the current study, we use Re_0 to define the discharge conditions from the gap. The discharge coefficient C was within the range of 0.6 and 0.75 in the current experiments.

Water discharged from a nozzle through a gap forms a liquid film which spreads on a disk. A laminar boundary layer is developed inside the liquid film, and the boundary layer eventually reaches the liquid surface. The authors clarified experimentally that, when the non-dimensional quantity of the radius position r was defined as, $r^* = (r/\sqrt{CDH})Re_0^{-1/3}$, the position where the boundary layer reaches the liquid surface is approximately $r^* = 0.25$ ⁽¹⁴⁾. Using this result, in the current study, we use the non-dimensional disk radius $r_e^* = (r_e/\sqrt{CDH})Re_0^{-1/3}$ which corresponds to the position of the disk edge radius r_e as an index to judge

whether or not the boundary layer reaches the liquid surface before it reaches the disk edge.

Furthermore, the authors previously reported that a laminar-turbulent transition similar to that occurring on a flat-plate boundary layer occurs on a disk when $Re_0 > 7.4 \times 10^4$, and that the transition point could be expressed as $r_t^* = 870Re_0^{-0.648}$ when the non-dimensional quantity of the transition point r_t (non-dimensional transition radius) r_t^* was defined by $r_t^* = (r_t/\sqrt{CDH})Re_0^{-1/3}$ ⁽¹²⁾. However, these results were obtained in experiments in which the gap distance H was 0.5 mm or larger and the stagnant pressure P was 80 kPa or lower. Therefore, we obtained the value of r_t^* under the conditions of current atomization experiments using the results of observation of laminar-turbulent transition points generated on a disk.

Table 1 lists the above-mentioned properties obtained as the flow conditions used for the photographs in the present paper. In the table, D_d is the disk diameter, and T is water temperature. For reference, the local Reynolds number at the disk edge $Re_e = U_e h_e / \nu$ and the Weber number $We_e = \rho U_e^2 h_e / \sigma$ are also listed. σ is the surface tension and U_e and h_e are the velocity of the liquid surface and the thickness of the liquid film, respectively, at the disk edge, where the velocity distribution in the liquid film flow on the disk is assumed to have a Watson-type distribution⁽¹³⁾.

3.2 Characteristics of the liquid film

With an increase in the discharge Reynolds number Re_0 , perforation occurs on a flat liquid film and the liquid film is atomized; Figs. 2(a)-2(f) show this process for a case when the disk diameter was 60 mm and the gap distance was 0.15 mm. The scale presented above each photo indicates the distance from the disk edge. When $Re_0 = 3.8 \times 10^4$ (Fig. 2(a)), the liquid film shows a smooth-surface laminar flow; since

Fig. 2 Feature of liquid surface ($D_d=60$ mm, $H=0.15$ mm)

the velocity of the liquid film is small, the liquid film is curved into a bell shape, and reaches the bottom of the casing 90 mm downstream of the disk edge.

When Re_0 is increased to 9.2×10^4 (Fig. 2(b)), a laminar-turbulent transition occurs 3–5 mm downstream of the disk edge. When the transition occurs, the liquid film is covered with microgranular waves which appeared white in the photographs due to the scattering of light rays on the liquid surface. Since these granular waves are converted to fairly large waves sufficiently downstream from the transition point, the liquid film is observed to be transparent. Three to five perforations are observed on the transparent liquid film, whose diameter increases with their distance from the disk edge. In addition, we can see that the liquid film forms a circular rim approximately 100 mm downstream of the disk edge, then is broken into fairly large drops.

When Re_0 is increased to 1.2×10^5 (Fig. 2(c)), the frequency of perforation increases, and the number of perforations existing on the liquid film increases. Accordingly, the rim shape becomes complex. When Re_0 is further increased to 1.4×10^5 (Fig. 2(d)), the frequency of perforation further increases and the boundaries between adjacent perforations are deformed into liquid strands approximately 40 mm downstream of the disk edge to form a net pattern. In addition, we can observe that these liquid strands break up into drops approximately 60 mm downstream of the disk edge. When Re_0 is increased to 1.6×10^5 or above (Figs. 2(e) and 2(f)), the frequency of perforation near the transition point increases significantly; as a result, perforations are not visually

distinguished and atomization of the liquid film immediately after the occurrence of the transition can be observed.

Spielbauer and Aidun⁽¹⁰⁾ reported that perforation occurred on a liquid film as a result of decreasing the liquid-film thickness to a size similar to foreign matters in the liquid, by observation of the perforation phenomena of a laminar liquid film spreading radially. However, as in the cases of the relatively small Reynolds numbers as shown in Figs. 2(b) and 2(c), the number of perforations does not depend significantly on the radial position; in addition, although the liquid-film thickness h_e at the disk edge does not change significantly with an increase in Re_0 (refer to Figs. 2(b) to 2(f) and Table 1), the frequency of perforation increases significantly. Therefore, the perforation observed in this study is not due to the thinning of the liquid film due to flow expansion, but to the localized thinning of the liquid film due to the disturbance immediately after the occurrence of the transition. This will be explained later.

Meanwhile, when a disk with a diameter of 60 mm was used, atomization immediately after the transition similar to that observed in Figs. 2(e) and 2(f) could be achieved for flow with a high Reynolds number, if the gap distance H was 0.3 mm or less. However, when $H > 0.3$ mm, atomization immediately after the transition could not be realized, even with the maximum Re_0 which could be obtained by the current experimental apparatus. The reason for this is as follows. Under such conditions, $re^* < 0.25$, i.e., the liquid film was detached from the disk edge before the laminar boundary layer reached the liquid

Fig. 3 Disintegration process ($D_d=60$ mm, $H=0.15$ mm)

surface; accordingly, the liquid film thickness is larger than the thickness of the boundary layer, and the disturbance immediately after the transition based on the inflection-type velocity distribution inside the liquid sheet did not become sufficiently high to generate a large number of perforations on the liquid film. Therefore, to atomize a liquid film immediately after the transition, it is necessary to form a liquid film in the case of which the laminar boundary layer reaches the liquid surface on the disk by means of discharging the water from a thin gap with high Re_0 , and to detach the liquid film from the edge of the disk.

To investigate the processes of liquid film breakup and drop formation, we took magnified photographs of a region from the disk edge to a point 30 mm downstream, for cases with liquid film characteristics similar to those observed in Figs. 2(d) and 2(f). Figures 3(a) and 3(b) show the photographs. The scale above the photos shows the distance from the disk edge. These photos were taken using a strobe with a flash duration of 2 μ s. In addition, a square grid of 0.3 mm intervals is placed 3 mm below the liquid film so that the outline and size of the perforations existing on the liquid film and the flying drops can be judged instantaneously.

When Re_0 is small as shown in Fig. 3(a), concentric ripple-like waves begin to appear 1 mm downstream of the disk edge. These waves which appear on a liquid sheet are called disturbance waves, i.e., D waves. The wavelength of the D wave agrees well with that of the unstable disturbance wave induced by the inflection-type velocity distribution inside the liquid film obtained from linear stability analysis⁽¹⁸⁾. For

this reason, the D wave can be considered to be a wave induced by disturbance which is amplified inside a liquid film. The D wave is amplified as it propagates downstream, and it transits to a turbulent flow 2 mm downstream from the disk edge. When the transition occurs, an extremely fine granular wave is generated in the liquid film. This wave is called a sandpaper-like wave, i.e., SL wave. Meanwhile, when looking at the point 7-mm downstream of the disk edge, a perforation of approximately 0.5 mm in diameter can be observed (arrow a in Fig. 3). In addition, at around 17, 23 and 27 mm downstream of the disk edge, the square grid is clearly visible, showing the presence of large perforations. However, no breakup of the liquid film or formation of drops is observed in Fig. 3(a).

When Re_0 is large as in Fig. 3(b), a large number of perforations are generated approximately 5 mm downstream of the disk edge (for example, arrow b in Fig. 3). These perforations rapidly expand and integrate 10–20 mm downstream of the disk edge and the liquid film breaks up into a large number of liquid aggregates. These liquid aggregates deform into moniliform liquid strands (arrow c in Fig. 3), and 20–30 mm downstream of the disk edge, the liquid strands break up once again to form drops with a diameter of 300–500 μ m (arrow d in Fig. 3). Thus, due to the integration of perforations, a liquid film breaks up to form liquid aggregations, then the liquid aggregations themselves break up to form drops of 300–500 μ m in diameter; this breakup process is called a liquid-aggregation disintegration-type breakup. Under the condition of Fig. 3(a), the formation of drops due to the liquid-aggregation disintegration-type breakup

Fig. 4 Transition and perforation process ($D_a = 60$ mm, $H = 0.15$ mm, $Re_0 = 1.6 \times 10^5$)

was confirmed to occur approximately 50 mm downstream of the disk edge.

To observe the process from the transition to perforation in further detail, we took magnified photographs of a region from the disk edge to a point 12 mm downstream, under similar flow conditions as in the case of Fig. 2(f). Figures 4(a) and 4(b) show the results. A strobe with a flash duration of $0.2 \mu\text{s}$ was located underneath the liquid film, and photographs were taken with a transmission light. By varying the irradiation angle of the strobe, perforation outlines and characteristics of the liquid surface are clearly visible in Figs. 4(a) and 4(b), respectively. In addition, a grid with 0.3 mm intervals was placed 3 mm below the liquid film in Fig. 4(a).

Observation of Figs. 4(a) and 4(b) revealed the following. D waves begin to appear approximately 1 mm downstream of the disk edge. The D waves rapidly change into three-dimensional shapes as their location advances downstream, and wavy irregularities are formed along the downstream direction (arrow a in Fig. 4). At a downstream distance of 2 mm from the disk edge, the convex parts of the wavy irregularities transit into a turbulent flow and are covered with fine granular waves (SL waves). The regions where the SL waves are generated appear black due to the blockage of light. In contrast, almost no SL waves are observed at the concave parts. This may be because at the concave parts, since the liquid film is thin and the effects of viscosity are strong, the disturbance inside the liquid film cannot be amplified. At a downstream distance of 4–6 mm from the disk edge, wavy convex parts form wavy liquid aggregates

where the SL waves are concentrated (arrow b in Fig. 4), and the concave parts between two liquid aggregates form relatively smooth thin membranes (arrow c in Fig. 4). In addition, striped irregularities which are assumed to be the residual D waves are observed at the thin membranes (arrow d in Fig. 4). At a downstream distance of 7 mm from the disk edge, we can confirm the presence of a perforation at the thin membrane (arrow e in Fig. 4). This perforation is considered to be attributable to the perforation due to SL waves existing at the boundary between the liquid aggregate and the thin membrane, or to the perforation due to the further thinning of the convex part of the striped irregularities existing in the thin membrane (arrow d in Fig. 4).

Observation of the rim of the perforation in Fig. 4 (arrow e) reveals the presence of microprojections, from which droplets of 20–30 μm in diameter are generated. In contrast, observation of the region 8–12 mm downstream of the disk edge reveals only the presence of liquid aggregates, with almost no thin membranes. In addition, a large number of projections with complex shapes were observed at the peripheral part of the liquid aggregates, and droplets of 20–30 μm in diameter were formed on these projections (arrow f in Fig. 4). These projections are assumed to be formed due to one of the following reasons: 1) fine SL waves are grown into projections, 2) a boundary part between two perforations existing in the liquid film part is deformed into projections when the perforations are integrated into one, or 3) the convex part of the striped irregularities (arrow d in Fig. 4) existing in the thin membrane remains at the

time of expansion of perforations. The formation of droplets with a diameter of $20 - 30 \mu\text{m}$ is observed clearly when the discharge Reynolds number is very high under which a liquid film is atomized immediately after the transition (Figs. 2(e) and 2(f)). The breakup mechanism to form droplets with a diameter of $20 - 30 \mu\text{m}$, due to the breakup of the microprojections existing on the rim of perforations and on the surface of the liquid aggregates as shown by arrows e and f in Fig. 4, is called a microprojection separation-type breakup, distinguished from the liquid-aggregates disintegration-type breakup.

Mansour et al.⁽⁸⁾ clarified that in a two-dimensional liquid sheet which was jet-discharged with parallel high-speed air flow from a nozzle, irregularities at a constant interval developed in the downstream and span directions on the liquid film immediately after the jet-discharge from the nozzle, and that grid-shaped convex parts and concave parts enclosed by the convex parts were formed, and these convex parts were also broken up into large drops while the concave parts were broken up into small droplets. However, it is reported that these irregularities cannot be formed in the absence of air flow. Therefore, the irregularities observed by Mansour et al. are judged to be formed by the interaction between the liquid film and the air flow, in which the mechanism of formation is different from that for liquid aggregates and membranes due to the laminar-turbulent transition observed in Fig. 4.

In this study, atomization due to microprojection separation type breakup is considered and explained in detail hereafter.

To investigate the expansion of perforations, deformation of liquid aggregates and the process of formation of drops due to microprojection separation-type breakup in further detail, we took high-speed continuous photographs of a flow. Figure 5 shows the results under flow conditions in which characteristics of liquid films similar to those in Fig. 2(f) are observed. The regions to be photographed are 12 mm downstream from the disk edge of 2 mm width in the peripheral direction, where a grid with 0.1 mm intervals is placed 3 mm from the bottom of the liquid film. Each frame of a photograph is rectangular and placed horizontally, and numbers ① to ⑦ in Fig. 5 correspond to each frame. The time interval between each frame is $41.7 \mu\text{s}$. In the figure, black parts represent liquid aggregates, white parts represent membranes, and parts where the grid is observed underneath the liquid film are perforations. Here, the parts where the grid is observed 1 mm downstream of or closer to the disk edge represent the laminar liquid films; in this region, the grid can be seen through the smooth laminar liquid

Fig. 5 High-speed photo of liquid film ($D_d=60 \text{ mm}$, $H=0.15 \text{ mm}$, $Re_0=1.6 \times 10^5$)

film. To clearly observe the states of transfer and deformation of liquid aggregates and liquid films as well as expansion of perforations, parts of the regions in Fig. 5 are schematically sketched and shown in Fig. 6. In Fig. 6, liquid aggregates are depicted in black, thin membranes in light gray, laminar liquid films in dark gray, and perforations in white. In addition, the upstream edge and downstream edge of the sketched region are moved with time, in accordance with the flow velocity.

Observation of the states of the liquid flow in Figs. 5 and 6 reveals that the liquid aggregate indicated by the arrow a in Fig. 6 ② exhibits a complex motion of rotation, inflection and breakup while moving in the downstream direction with time. In addition, perforation occurs at the membrane 4 mm downstream of the disk edge (arrow b in Fig. 6 ②), and the generated perforations move downstream while expanding. The speed of this movement is calculated to be approximately 30 m/s from the time interval of the frames. Incidentally, the authors previously clarified from LDV measurement that the speed in the radial direction of a liquid sheet after the laminar-turbulent transition was 75 - 85% that of the liquid surface U_e ⁽¹⁹⁾. When this result is applied to the conditions in Fig. 5, the speed of the liquid sheet is calculated to be 28 - 32 m/s, indicating that the perfora-

Fig. 6 Schematic of high-speed photo shown in Fig. 5

tions move at a speed similar to the liquid sheet.

In Figs. 5 and 6, we can see that the boundary between a perforation and a liquid aggregate has a complex shape with a large number of microprojections. These microprojections are assumed to be formed by the following: micro-deformations on the surface of the liquid aggregate generated by SL waves grow into projections, due to the shearing stress between air-liquid or a centrifugal force accompanying the rotation motion of the liquid aggregate; or, the convex parts of the wavy irregularities existing in the membranes shown by the arrow d in Fig. 4 are left during expansion of the perforations. After formation of the projections, they break away from the liquid aggregate and droplets of 20–30 μm in diameter are formed (arrow c in Fig. 6: microprojection separation-type breakup). Observation of the expansion of the perforations shows that they expand mainly in the thin membrane, and frequently integrate 8 mm downstream of the disk edge in the thin membrane. In addition, the rims of the perforations have a more complex shape after integration, and we can observe that a large number of microdrops are formed from the microprojections on the rim of the perforations (microprojection separation-type breakup). Although not clearly shown in Figs. 5 and 6, other photography results show that fine liquid strands which constitute boundaries of the perforations are broken up into microdrops during integration of the

Fig. 7 Laminar-turbulent transition on a stationary disk ($D_d=80$ mm, $H=0.25$ mm, $Re_0=3.1 \times 10^5$)

Fig. 8 Laminar-turbulent transition on a rotating disk ($D_d=70$ mm, $H=0.30$ mm, $Re_0=2.1 \times 10^5$, Disk rotational speed: 125 rps)

perforations (microprojection separation-type breakup).

3.3 Effects of transition on a disk on atomization

The authors previously reported that laminar-turbulent transition similar to that observed in the boundary layer of a flat plate occurs in a liquid flow with a high discharge Reynolds number on a still disk⁽¹²⁾. In addition, we clarified that when a disk is rotating, laminar-turbulent transition derived from the instability of a torsional boundary layer formed on the disk occurs⁽²⁰⁾. In this study, we investigated the effects of laminar-turbulent transition occurring on a disk on the perforation of a free liquid film. Figure 7 shows the result for the case of a still disk with disk diameter $D_d=80$ mm, gap distance $H=0.25$ mm and, discharge Reynolds number $Re_0=3.1 \times 10^5$; Fig. 8 shows the result for the case of a rotating disk with a disk diameter $D_d=70$ mm, $H=0.30$ mm, $Re_0=2.1 \times 10^5$ and 125 rps. From Figs. 7 and 8, we can observe that the laminar-turbulent transition occurs 2 mm upstream of the disk edge and the turbulent liquid film flows from the disk edge into the air. In such a case,

Fig. 9 Flow condition for atomization induced by transition

although the liquid surface is covered with fine granular waves, a grid placed below the liquid film cannot be observed, indicating that perforation does not occur. This is because if laminar-turbulent transition occurs once on the disk, the transition induced by the inflection-type velocity distribution inside the liquid sheet can no longer occur. Therefore, to atomize a liquid sheet by the microprojection separation-type breakup, it is necessary to induce laminar-turbulent transition due to the inflection-type instability downstream of the disk edge.

3.4 Conditions of atomization

The flow conditions of atomization of a liquid film induced by microprojection separation-type breakup immediately after laminar-turbulent transition for the case of a still disk were investigated in terms of liquid film characteristics using photographs. Figure 9 shows the results. Here the experiments were performed for water temperature of $15^{\circ}\text{C} \pm 3^{\circ}\text{C}$. In Fig. 9, the horizontal axis represents gap distance H , and the vertical axis represents stagnant pressure P . Disks with $D_d = 50, 60, 80$ and 100 mm were used in the experiments, and the solid lines connecting the data of each disk in Fig. 9 represent the lower-limit pressure under which microprojection separation-type breakup occurs. In addition, the four dotted lines inclined to the right represent the condition of $r_e^* = 0.25$ in which an entire liquid film has a boundary-type velocity distribution at the disk edge, and a pressure larger than this curve shows that, at this pressure, the boundary-type velocity distribution is not yet fully developed at the disk edge. In contrast, the four broken lines inclined upward toward the right in Fig. 4 represent a lower-limit pressure under which a transition occurs on the disk. These broken lines were obtained from other transition experiments using a disk with $D_d = 160$ mm. For reference, the previously reported conditions under which transition occurs at the disk edge, which were obtained using an experimental

equation $r_t^* = 870 Re_0^{-0.648}$ for the non-dimensional transition radius r_t^* by the authors, were expressed with four thin lines. The stagnant pressure obtained from the present experiments is much larger than those reported previously; in the present experiments, the transition on the disk occurs further downstream than the radius predicted by the experimental equation. In addition, the difference between these two increases with decrease in gap distance. Based on the above results, atomization due to microprojection separation-type breakup immediately after the laminar-turbulent transition occurs in the hatched region enclosed by three curves: solid, dotted and broken lines. Accordingly, to realize atomization by transition using Fig. 9, a thin gap with a high stagnant pressure is required when the disk diameter is small. In addition, with a decrease in the disk diameter D_d , the range of gap distance for the realization of atomization decreases.

4. Conclusions

Water is radially discharged from a nozzle through a small gap between the nozzle and a disk to form a liquid film in which laminar boundary layer type velocity distribution is developed even on the liquid surface, and the liquid film flows radially into the air. In the thus formed radial liquid sheet, a large number of perforations are generated immediately after the laminar-turbulent transition when the liquid film is thin and the discharge Reynolds number is large, and as a result, the liquid film is atomized. Detailed observation of the point near the occurrence of transition revealed that the transition, perforation and atomization of the liquid film occur by the following process.

(1) Appearance of the rippled concentric waves (D waves) and formation of wavy irregularities by three-dimensional conversion of the D waves.

(2) Concentrated formation (laminar-turbulent transition) of the fine-granular waves (SL waves) at the convex part and formation of the wavy liquid aggregates by concentration of the granular waves. Formation of thin membranes due to the thinning of the concave parts of the film.

(3) Perforation at the membranes and expansion of the perforations. Formation of droplets of $20 - 30 \mu\text{m}$ in size by separation of the microprojections at the peripheral parts of the liquid aggregates (microprojection separation-type breakup).

(4) Deformation of the liquid aggregates into moniform liquid strands and formation of drops of $300 - 500 \mu\text{m}$ in size by the breaking of the liquid strands (liquid aggregate disintegration-type breakup).

In addition, we clarified that when transition occurs on a disk due to a high discharge Reynolds number or disk rotation, perforation is highly suppressed; we also showed conditions in which atomization occurs due to microprojection separation-type breakup.

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References

- (1) Squire, H.B., Br. J. Appl. Phys., Vol. 4 (1953), p. 167-169.
- (2) Hagerty, W.W. and Shea, J.F., J. Appl. Mech., Vol. 22 (1955), p. 509-514.
- (3) Fraser, R.P., Eisenklam, P., Dombrowski, N. and Hasson, D., A.I.Ch.E.J., Vol. 8 (1962), p. 672-680.
- (4) Dombrowski, N. and Johns, W.R., Chem. Eng. Sci., Vol. 18 (1963), p. 203-214.
- (5) Arai, K. and Hashimoto, H., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 463, B (1984), p. 856-863.
- (6) Rangel, R.H. and Sirignano, W.A., Phys. Fluids A, Vol. 3 (1991), p. 2392-2400.
- (7) Arai, K. and Hashimoto, H., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 470, B (1984), p. 3336-3342.
- (8) Mansour, A. and Chigier, N., Phys. Fluids A, Vol. 2 (1990), p. 706-719.
- (9) Lozano, A., Call, C.J., Dopazo, C. and Olivares, A. G., Atomization and Sprays, Vol. 6 (1996), p. 77-94.
- (10) Spielbauer, T.M. and Aidun, C.K., Atomization and Sprays, Vol. 4 (1994), p. 405-436.
- (11) McCreery, G.E. and Stoots, C.M., Int. J. Multiphase Flow, Vol. 22 (1996), p. 431-452.
- (12) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 452, B (1984), p. 974-981.
- (13) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 452, B (1984), p. 982-989.
- (14) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 452, B (1984), p. 1126-1133.
- (15) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 452, B (1984), p. 1136-1143.
- (16) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 460, B (1984), p. 3176-3183.
- (17) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 53, No. 491, B (1987), p. 2007-2014.
- (18) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 53, No. 492, B (1987), p. 2348-2355.
- (19) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 54, No. 498, B (1988), p. 361-366.
- (20) Azuma, T. and Hoshino, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 55, No. 516, B (1989), p. 2139-2147.