Microgravity experiments on ISS in order to examine a new atomization theory discovered through normalgravity and microgravity environments

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Abstract. In order to elucidate turbulent atomization processes, many studies by the use of a liquid jet issuing from a circular nozzle have been conducted for a long time. Although Rayleigh’s instability has been regarded as the only determinant for the breakup of the liquid jet, the source of the disturbances has been unclear and thus the physical explanation of experimental results was impossible. From our experimental and numerical approaches under normalgravity and microgravity environments, it was found that the breakup by the short-wave mode occurs around the tip of the liquid jet without any disturbances. The long-wave mode is caused by the existence of a nozzle exit through a self-closed breakup cycle sustained inherently by the capillary waves emanated from the tip of the liquid jet after every breakup. Our further experiments revealed the existence of the relaxation region which gives a reasonable explanation of the extremely large breakup length. In addition, the two-valueness of the breakup length was found through a lot of experimental results. Establishment of a new breakup theory enable to explain all of experimental results requires long-period microgravity environments and the currently-projected experiments on ISS are introduced in the present paper.

1. Introduction

Liquid atomization processes are very important in engineering applications using liquid fuel such as rocket engines, gas turbines including jet engines, automobile engines and so on. In addition, this technology is essential to ink-jet printers. Against such practical backgrounds, many studies on liquid atomization processes have been conducted. A snapshot representing typical atomization processes is depicted in figure. 1. A high-speed liquid jet is injected from a circular nozzle. Liquid atomization processes are categorized into three phases. The nondimensional number characterizing each phase is gas Weber number defined as

\[ W_{eG} = \frac{\rho_G U^2 a}{\sigma} \]  

where \( \rho_G, U, a \) and \( \sigma \) correspond to gas density, velocity difference between gas and liquid, a radius of liquid jet and surface tension coefficient, respectively. Gas Weber number corresponds to the ratio of gas dynamic pressure to surface tension in two-phase flow fields. Just downstream of the nozzle exit, denoted as the region A in figure. 1, the small-scale disturbances are induced on the liquid surface.
Since gas Weber number in the region A is sufficiently larger than $O(1)$ due to the large velocity difference, the effects of surface tension is small and the formation of such disturbances are dominated by the characteristics of turbulence. Such disturbances cause the formation of the fine liquid ligaments in the region B, where gas Weber number is $O(1)$ due to the small scale of the liquid ligaments and the small local velocity difference. Therefore, the effects of surface tension dominate the behaviour of the liquid ligaments and their breakup. Gas Weber number of the flow field occupied by many small droplets formed from liquid ligaments is smaller than $O(1)$. In order to predict the characteristics of droplets (e.g. drop-size distribution), the flow field in the region B must be correctly understood. Since such flow field is too high-speed and small to be observed directly, a certain approach has been adopted for a long time. A fine liquid ligament is replaced by a low-speed and large-scale liquid jet in accordance with Weber’s analogy. In conventional experiments, a liquid jet was injected from a circular nozzle along the direction of gravity as depicted in figure 2. Although the effects of gravitational acceleration must be taken into account, they have been unnoticed for a long time. The corresponding nondimensional number is Bond number, which is expressed as follow.

$$Bo = \frac{\rho \alpha^2 g}{\sigma} \quad (2)$$

$\rho$ is liquid density. The scale of the original liquid ligaments is so small that the corresponding Bond number is essentially small. However, such traditional replacement can make Bond number larger than that of the original liquid ligaments, which has led to the misunderstanding of the physics underlying

**Figure 1.** A schematic of typical liquid atomization processes. The region surrounded by a dotted circle corresponds to the target of the present study.

**Figure 2.** A typical snapshot obtained through conventional experiments.

**Figure 3.** Successive images obtained from a microgravity experiment under high-pressure condition.
the liquid atomization processes for a long time. The most simple and effective way is to remove the effect of gravity. From this viewpoint, Umemura et al. [1] carried out the experiments as illustrated in figure 2 under microgravity environments. In order to realize the flow field with small gas Weber number and composed of the liquid jet large enough to get snapshots with sufficient temporal and spatial resolution, liquid SF₆ was injected from a circular nozzle into high-pressure N₂ atmosphere. The typical snapshots obtained from the microgravity experiments are shown figure 3. In figure 3, the radius of the nozzle and the ambient pressure were 0.2 mm and 6.0 MPa, respectively. Gas Weber number is 0.133 and thus the flow field around liquid ligaments in turbulent atomization was well simulated. The mechanism conventionally used for the explanation of liquid jet disintegration is that proposed by Rayleigh [2]. According to the theory of Rayleigh, the long-wave surface deformation is the only determinant for the breakup of the liquid jet in a laminar case. However, the wavelength observed in the microgravity experiments is smaller even if the effect of gas dynamic pressure and viscosity are considered [3-5] and the breakup configuration is so different from that derived from the theories of Rayleigh. This breakup configuration was named as ‘short-wave mode’ by Umemura [6]. What is important is the fact that the breakup in the short-wave mode occurs without any disturbances as long as there exist the tip of the liquid jet. On the other hand, the breakup due to the long-wave disturbances, namely ‘long-wave mode’, inevitably requires some kind of disturbances. The breakup in the long-wave mode is usually observed even in laminar flow fields. In such cases, the sources of the disturbances were unclear in the theories of Rayleigh and have been usually attributed to the ones existing inside of a nozzle or in nature according to the previous researches. Depending on the experimental conditions, such approaches lead to the incorrectly small initial amplitude of the disturbances at the nozzle exit. This value is unable to give reasonable answers to the repeatability of the experimental results. In order to investigate the breakup processes of a liquid jet in detail, authors have been carried out the experiments as illustrated in figure 2 by the use of pure water not only on normal gravity but also on microgravity environments. From our experimental results and numerical approaches [6], the periodic breakup of a liquid jet is sustained through a self-closed breakup cycle requiring inherently no external disturbances. Keys to the self-closed breakup cycle are the capillary waves emanated from the tip of liquid jet and the behavior of the waves at nozzle exit. In addition, the further experiments elucidated the determinants other than the waves existing on the liquid jet. In order to investigate the further physics underlying the breakup of the liquid jet, the long-term microgravity experiments on International Space Station (ISS) are currently projected with the aid of JAXA. In the present paper, an outline of our breakup theory and the currently-projected space experiments are provided along with the several experimental results.

2. An outline of a new breakup theory

2.1. Capillary and unstable waves

First of all, let us consider waves on a liquid jet issuing from a circular nozzle by the use of a flow field of a liquid column with an infinite length. Here the assumptions are adopted that the effects of gas pressure, viscosity and velocity distribution of a liquid jet are negligible for simplicity. In addition, the coordinate moving at the same speed as that of the liquid jet are used. These assumptions give the similar analyses proposed by Rayleigh [2]. This analysis corresponds to the pressure imbalance between neck and bulge parts of the small-amplitude surface deformation on an infinite liquid column. The surface deformation $\delta$ is expressed in a nondimensional form as follow,

$$\frac{\delta}{\bar{a}} = \frac{a}{\bar{a}} \exp\left(i(kx - \omega t)\right)$$

(3)

where $a$, $\bar{a}$, $k$ and $\omega$ are an initial radius of a liquid column, an initial amplitude, wavenumber and angular frequency, respectively. The following dispersion equation is derived by the linearization of the equations of continuity and motion around the basic flow field and by the appropriate boundary conditions.
\( \left( \frac{\omega a}{V} \right)^2 = -\left(ka\right)^2 - \left(ka\right)^2 \frac{I_1(ka)}{I_0(ka)} \) \hspace{1cm} (4)

\[
V = \sqrt{\frac{\sigma}{\rho a}} \]

(5)

\( I_n(x) \) is the n-th modified Bessel function. \( \omega \) is a pure imaginary number and corresponds to the temporal growth rate of the disturbances. Due to the local curvature of the generating line and the circumferential directions, the pressure differences between the neck and the bulge parts are generated. When the nondimensional wavelength \( \lambda/a = 2\pi/(ka) > 2\pi \), the flow field is unstable. Physically speaking, the pressure at the neck parts exceeds that at the bulge parts. This pressure difference generates the liquid flows from the neck parts into the bulge parts and finally leads to the breakup of the liquid column. Such waves are called as unstable waves. According to the linear stability analysis, the disturbance with \( \lambda/a = 9 \) gives maximum growth rate. Growth of the unstable wave by numerical simulation is illustrated in figure 5. The governing equation adopted is the axially-symmetric incompressible Navier-Stokes equation for nonevaporating liquid and gas. The effect of the surface tension was expressed by the continuous surface force method [7]. The flow field was assumed to be periodic in the axial direction. The details of the numerical methods were described in [8]. A sinusoidal surface deformation with \( \varepsilon/a = 0.01 \) was added to a stationary liquid column. The axially-elongated surface configuration of the neck part and the small satellite formed after the breakup between the main droplets are characteristics of the breakup in the long-wave mode. The breakup configuration illustrated in figure 4 is quite different from that in figure 3 as noted above.

In the case where \( \lambda/a < 2\pi \), the solutions corresponding to the neutral propagative capillary wave can be obtained. Their phase speed \( c_R \) can be obtained from the equation (4) and expressed as follow:

\[
\frac{c_R}{V} = \sqrt{\frac{I_1(ka)}{I_0(ka)} \left( \frac{ka - 1}{ka} \right)} \]

(6)

From (6) it is clear that the capillary waves with the shorter wavelength give the larger phase speed and this property is important for the realization of the self-closed breakup cycle noted later. In the linear stability analysis, only the solutions corresponding to a single capillary wave component is obtained. Although the properties of the unstable and the capillary waves are explained here, it is still unclear how such waves, in other words, ‘disturbances’ are generated. In the next subsection, the sources of disturbances and the breakup in the short-wave mode are investigated through a problem related to contraction of a liquid column.

2.2. Short-wave mode and a source of capillary waves

In order to investigate the short-wave mode and the role of the capillary waves driven by a liquid tip, a
numerical simulation of an initially static liquid column were carried out as shown in figure 5 (a). The same governing equations in the previous subsection were adopted. The conditions of the flow field are similar to those of our microgravity experiments. The definitions of the characteristics parts are illustrated in figure 5 (b). The breakup of the liquid column occurs at approximately $tV/a = 20$ and the surface configuration around the breakup point is quite similar to the experimental results in figure 3. Since the tip bulb is attracted due to surface tension of the liquid column, it moves upstream with ‘swallowing’ its upstream liquid and enlarging its size. The resulting pressure decrease in the tip bulb observed in figure 5 (a) is necessary for the breakup in the short-wave mode. As a necessary condition for the breakup in the short-wave mode, the radius of the tip bulb must be larger than 2a. In addition, the linear surface configuration just upstream in the 1st neck observed in figures 3 and 5 (a) also plays an important role in sustaining the liquid flow into the tip bulb through its sufficient pressure rise. The breakup in the short-wave mode has no direct relationship to liquid issue speed and has a specific frequency.

As the tip contraction occurs, the capillary waves are emanated and propagate upstream as illustrated in figure 5. Although inherently a group of waves propagates due to its dispersive nature, the propagation speed of each capillary wave component follows the equation (6) [9]. By focusing on the locations of the neck parts, the movement of the capillary wave components is tracked as illustrated in figure 5 (c). Due to their dispersive nature, the capillary wave components gradually increase its wavelength with decreasing their propagation speed. Finally their propagation speed gradually reach an asymptotic value [6], in other words a steady-capillary wave is formed. $V$ in the equation in (5) corresponds to the analytically-derived asymptotic speed and nearly equal to the contraction speed of the liquid column. The gray line in figure 5 (c) corresponds to the contraction speed and its agreement with the analytical one is satisfactory. During the contraction process, the total surface area of a liquid column decreases in accordance with the minimum surface area principle. The decrease in the surface energy is transferred upstream through the capillary wave [6]. By adding the jet issue speed $U$ to the flow field noted above, we can discuss a liquid jet issuing from a nozzle. However, unless the effects of nozzle remain clear, the further discussion is impossible. The conversion of the capillary waves reaching at a nozzle exit is discussed in the following subsection.

2.3. A self-closed breakup cycle

It was clarified that capillary waves propagate upstream due to contraction of a liquid tip in the previous subsection. The Capillary waves with large propagation speed and small wavelength can

![Figure 5](image-url)

**Figure 5.** (a) Numerical simulation of contraction of a liquid column. (b) Definitions of the characteristic parts on the contracting liquid column. (c) Upstream propagation of capillary waves emanated from the liquid tip.
reach a nozzle exit in the case of a liquid jet. In addition, although the situation including only one breakup is considered in the previous subsection, capillary waves would be emanated after each breakup not depending on breakup modes. Through Doppler-shift at the nozzle exit the wavelength of the capillary waves becomes larger \[6, 9\]. The properties of the resulting wave can be described through the following equations,

\[
2\pi \left( \frac{f a}{U} \right) = \left( c_R (ka) - \frac{U}{V} \right) (ka) = \left( \frac{c_R (ka)}{V} + \frac{U}{V} \right) (k'a) \quad (k'a > 1) \tag{7-1}
\]

\[
2\pi \left( \frac{f a}{U} \right) = \left( c_R (ka) - \frac{U}{V} \right) (ka) = \left( \frac{U}{V} \right) (k'a) \quad (k'a < 1) \tag{7-2}
\]

where \( k'a \) and \( f \) correspond to nondimensional wavenumber of a wave component subjected to Doppler-shift and its frequency, respectively. In addition, \( fa/U \) corresponds to Strouhal number. For example, \( U/V = 2.0 \) case gives a solution of \( \lambda/a = 1.10 \) under the assumption that the most unstable waves noted above dominate the breakup characteristics. At least in laminar injection cases, there always exist the capillary waves converted into the unstable waves through Doppler-shift. In other words, the unstable waves are spontaneously generated at the nozzle exit without any external disturbances. In addition, ‘reproduction’ of the waves at the nozzle exit also has an important role for sustaining the formation of the unstable waves \[6\]. Once the waves convecting (or propagating) downstream are formed just at the nozzle exit, the same waves continues to be formed. The amplitude of the waves formed owing to the reproduction process becomes smaller as time passes in the case of \( U/V > 1 \). However, the continuous generation of the unstable waves is possible by the capillary waves emanated after each breakup. The concept explained above corresponds to a self-closed breakup cycle of a liquid jet proposed by Umemura \[6\]. By looking for answers not to unidentified disturbances but to the capillary waves generated by the liquid jet itself, the repeatability of experimental results can be explained well. However, not all of experimental results can be explained only by the use of the self-closed breakup cycle. The additional characteristics of a liquid jet are described in the section 4 along with our experimental results.

3. Experimental setup and image processing

3.1. Experimental setup

Almost all of the following experimental apparatuses were commonly used in both our normalgravity and microgravity experiments. A schematic of the experimental setup is illustrated in figure 6. A backlight method was used for obtaining clear successive images of a liquid jet. As a light source, an array of high-intensity LEDs made by Opto Supply was arranged in the test section. Luminosity and diffusion angle of each LED are 6000 mcd and 60 deg, respectively. In order to obtain brightness distribution as uniform as possible, a holographic diffuser made by Edmund Optics was adopted. A variable resistance incorporated in the LED circuit can finely modulate the brightness. The light source is driven by direct current supplied from the experiment facilities. Images of a liquid jet were taken by a high-speed camera. A planar aluminum mirror was used to obtain an appropriate optical path. A high-speed camera made by Photron was adopted owning to its performance and impact resistance necessary for the experiments in a drop tower. Exposure time was set as 1/15000 s and frame rate was set as 4000 fps. The length able to capture in the liquid issue direction can be changed approximately from 130 mm to 200 mm by modulating the optical system. Images stored in the high-speed camera were downloaded into a PC through an optical fiber cable. Frame rate 4000 fps corresponds to approximately 4.1 s. After flow field reaches a quasi-steady state, a start trigger was transferred to the high-speed camera. Pure water was stored in a syringe and issued through a nozzle part. The syringe and the nozzle part were connected by the use of a tube made by Teflon. Water installed in the syringe was pushed by a rack-and-pinion system made by Oriental motor. There is a possibility that controlling flow rate by the use of a flow meter cannot follow pressure fluctuations at a nozzle exit. Since the radii of the syringe and the nozzle exit can be measured in advance, water flow
rate itself can be controlled by controlling the moving speed of the rack. It takes at most 2 s to achieve a constant-speed movement of rack. A liquid recovery unit was used only in the normal gravity experiments. The nozzle parts made of stainless were composed of an upstream entrance region and a downstream nozzle section. The length and the radius of the entrance region are 20 and 4.35 mm, respectively. The thickness of the nozzle section is 0.5 mm. The radii of the nozzle exit are 0.39, 0.56, 0.80 and 1.03 mm, respectively. Although the experimental space on ISS is a little smaller than that on the drop tower and the parabolic flight facilities the authors have used so far, the fundamental arrangement can be applied directly to the space experiments.

3.2. Image processing

Many images with resolution $j_{\text{max}} \times i_{\text{max}} = 1024 \times 128$ pixel can be obtained after each experiment as depicted in figure 7. In order to extract information related to the breakup process of a liquid jet, its surface configuration must be correctly captured. Since the number of successive images obtained from one experiment exceeds 10,000, virtual judgement is impractical. Appropriate methods tracking a liquid tip are necessary. The tip-tracking method previously used in our studies is described in [10] in detail. By the use of the minimum and the maximum (strictly speaking, the mode value of the background) brightness of raw images, new ones with the larger contrast were used for detecting the location of the liquid tip in this method. However, in the less resolved case, unphysical oscillations of the tip location were caused by the small non-uniformity of backlight and by the existence of small satellites formed between main droplets. In addition, there is a difficulty in determining the threshold value of the brightness determining the liquid tip. Instead of this method, another method was adopted in which the new images are constructed by subtracting the background brightness from the original images as illustrated in figure 7 (b). This procedure reverses the brightness of the original images and thus the liquid surface is expressed by the white region. The minimum brightness at the $j$th location, $B_{\text{min}}(j)$, can be obtained by comparing the brightness from $i = 1$ to $i = i_{\text{max}}$. Detecting a sudden decrease in $B_{\text{min}}(j)$ from $j = j_{\text{nozzle}}$ to $j_{\text{max}}$, the liquid tip can be specified as $j_{\text{tip}}$. It was found that the images obtained through this method are less susceptible to the non-uniformity of the backlight and to the effects of the satellites. A typical time history of the tip location obtained through the procedures denoted above is shown in figure 7 (c). During one experiment, breakup occurs many times. A sudden decrease in the tip location corresponds to one breakup. Breakup length is defined as the length from the nozzle exit to the liquid tip just after a certain breakup as illustrated in figure 7 (b). One breakup length plotted as one point in graphs in the section 4 is the mode value evaluated by the use of all breakup information obtained from one experiment. Together with the mode value, the standard deviation is also evaluated and expressed as error bars.
4. Experimental results

4.1. Difference in breakup configuration due to gravity

Typical snapshots obtained from the experiments under normalgravity and microgravity environments are listed in figure 8. The nozzle of $a = 1.03$ mm was used in each experiment. In all images, the brightness is modulated for improvements in the visualization. Hereinafter, $U/V$ is defined as the ratio of cross-sectional average liquid issue speed at the nozzle exit to the analytical tip contraction speed expressed in the equation (5) unless otherwise noted. Under microgravity environments, the critical $U/V$ determining the dominant breakup mode is nearly 1.58. This value can be derived by considering the displacement of the 1st neck part and the liquid flow rate entering the tip liquid bulb during one breakup [6]. In the $U/V = 1.98$ and 2.49 cases, the long-wave mode fixes the breakup length. The significant difference in the breakup configuration is observed in the $U/V = 1.23$ and 1.50 cases depending on the existence of gravitational acceleration. Local $U/V$ gradually increases in the axial direction due to gravitational acceleration (Bond number is approximately 0.146 in figure 8) and finally exceeds 1.58. In this case, the unstable waves convecting downstream increase their amplitude and finally the breakup length is fixed by the long-wave mode even in the case of $U/V < 1.58$. In the case where the nozzle of $a = 0.39$ mm was used, the short-wave mode can fix the breakup length even under normalgravity environment due to the small Bond number [6].

The larger liquid issue speed causes the larger breakup length intuitively. However, this intuition

Figure 7. Schematics of image processing. (a) Typical images obtained from an experiment. (b) Images obtained through background elimination. The white vertical lines indicate the tip locations judged by our program. The figures on the right upper side correspond to frame number. (c) Typical time history of the tip locations.

Figure 8. Difference in breakup configurations caused by gravitational acceleration. A nozzle of $a = 1.03$ mm was used in each experiment.
does not always hold judging from the images shown in figure 8. Either the effects of the gas dynamic pressure or viscosity [3-5] are unable to explain this phenomenon correctly. The flow field shown in figure 8 is inherently laminar according to the turbulence standard of Reynolds, \( Re_D < 2300 \). This is true judging from their smooth surface configuration. Turbulence inside of the nozzle alone is not the correct answer to such phenomenon. In order to investigate such phenomenon, a lot of experiments were carried out by the use of the several nozzles and the the results are shown in the next subsection.

4.2. Existence of relaxation region

The breakup length obtained from normal gravity experiments by the use of the nozzles of \( L_n = 30 \text{ mm} \) is shown in figure 9. Experiments by the use of a certain nozzle were repeatedly conducted at least twice in order to examine their repeatability. The experimental results in figure 9 show a sufficient agreement with the ones conducted by the other researchers [11, 12], which suggests the existence of the breakup mechanism independent of the disturbances inside of nozzles at least in laminar cases. The jumps in the breakup length around small \( U/V \) are caused due to gravitational acceleration as noted in the previous subsection. Figure 9 shows that a lot of experimental results can be classified into two breakup modes, namely long distance breakup (LDB) and short distance breakup (SDB) modes. The breakup length for the nozzles of the small radius has a tendency to belong to the LDB mode and vice versa for the nozzles of the large radius. This tendency is deeply related to the flow field inside of the nozzle. Flow entering a circular tube goes downstream with developing its velocity distribution. If length of a tube is sufficiently large, the velocity distribution approaches that of well-known Hagen-Poiseuille flow perfectly in a laminar case. Since this tendency is characterised by Reynolds number \( Re_D = 2Oh(U/V) \), the velocity distribution of the liquid issuing from the nozzles of smaller radius is likely to approach such velocity distribution. In the previous researches the effects of velocity distribution was suggested [5, 13]. However, the instabilities induced by such flow field have not been investigated in detail. Umemura [6] performed the linear stability analysis as to the liquid flow with such velocity distribution. It was found that the increase in \( \Delta(U/V) \) gives the smaller growth rate of the unstable waves and finally the unstable waves disappear in the case of \( \Delta(U/V) > 2.0 \). Here \( \Delta(U/V) \) corresponds to the nondimensional maximum difference of the parabolic velocity distribution. \( \Delta(U/V) = 0 \) corresponds to the uniform velocity distribution. This effect is understood as a situation where a rigid body (corresponding to a limit of flow with larger momentum) is inserted into liquid. In addition, even if the velocity distribution is perfectly that of Hagen-Poiseuille flow, viscosity of liquid relaxes the velocity distribution as goes downstream and finally nearly uniform velocity distribution is achieved. This suggests that the breakup length shown in figure 9 includes a ‘relaxation region’ which is inherently independent of the growth of the unstable wave. In figure 9, a Boussinesq line is also shown on the assumption that the velocity relaxation is the opposite phenomenon to the development of the velocity distribution inside of the nozzle. Although this is a crude assumption, it is found that the relaxation region occupies the large part of the breakup length. Since the liquid ‘surface’ velocity increases gradually within the relaxation region, the capillary waves propagating upstream are subject to Doppler-shift and their wavelength gradually become larger during their upstream propagation. The larger wavelength corresponds to the smaller propagation speed. The decrease in the propagation speed of the capillary waves, which is caused by the increase in their wavelength, changes their propagation direction into the downstream direction. The increase in the wavelength continues during their downstream propagation and finally their nondimensional wavelength exceeds 1 [6]. Such waves coming back to a uniform velocity region obtains the nature of the unstable wave. This suggests that the relaxation region is identical to the nozzle exit. In fact, if we evaluate an initial amplitude without considering the relaxation region, an invalid value smaller than an intermolecular distance is obtained for the experimental results by the use of the nozzle of \( a = 0.39 \text{ mm} \). Such unphysically small value cannot explain the sufficient repeatability and the independency of experimental apparatuses.

As \( U/V \) increases, \( Re_D \) approaches 2300 which is the criterion classifying laminar and turbulent pipe flows investigated by Reynolds. The intermittent change in the breakup length, which corresponds to
the large error bars in figure 9, is thought to be caused by the vortices shed from the separation bubble formed at the nozzle entrance region. In the case where $U/V$ exceeds a certain value, the transition into the fully developed turbulent flow occurs within the nozzle. In addition to the more uniform velocity distribution, the disturbances shed from the nozzle dominate the breakup of the liquid jet and the sudden decrease in the breakup length accompanied by so irregular and large-amplitude surface deformation is observed as illustrated in figure 10. The value of the critical Reynolds number 2300 may not be directly applicable to our experimental results since this value was determined from the experimental results by the use of sufficiently long pipes. In our experiments, the length of the nozzle is comparatively small and the flow field inside of the nozzle is subject to the disturbances coming from downstream. On the contrary, the SDB mode is not always dominated by the turbulence inside of the nozzles. The surface configuration of the liquid jet classified into the SDB mode seems different depending on the radii of nozzles. In order to examine the breakup characteristics in the SDB mode, let us focus on the breakup length obtained from the experiments by the nozzle of $a = 1.03$ mm.

### 4.3. Two-valueness of breakup length

It is observed that the breakup length for the nozzle of $a = 1.03$ mm takes two values for a certain liquid issue speed as illustrated in figure 11. Each value is categorized into either the LDB or the SDB mode. The typical images for $U/V = 1.78$ are shown in figure 12. The critical $U/V$ corresponding to $Re_D = 2300$ in the case of $\mu = 1.10$ cP ($Oh = 4.00 \times 10^{-3}$) is 4.60. Since $U/V$ is smaller than the half of the critical value and both of liquid jet seems laminar judging from the smoothness of the surface configurations and the regular breakup pattern, it is unlikely that the SDB mode is not always

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**Figure 9.** Difference in breakup process caused by gravitational acceleration. A nozzle of $a = 1.03$ mm was used in each experiment. LDB and SDB correspond to long breakup distance and short breakup, respectively.

| $a$  | $L_b/a$ | $\mu$ (cP) | $L_n$ (mm) |
|------|---------|------------|------------|
| 0.39 | 0.39    | 0.738      | 30         |
| 0.56 | 0.834   | 1.29       | 0.39       |
| 0.80 | 0.738   | 0.56       | 0.80       |
| 0.80 | 0.738   | 1.19       | 1.03       |

**Figure 10.** Typical images obtained from experiments by the use of a nozzle of $a = 0.39$ mm.
dominated by turbulence. Such laminar SDB case is observed in the experimental results of the nozzles of comparatively small $L/a$. If the velocity distribution inside of the nozzle does not fully develop at the nozzle exit, the length of the relaxation region would be small and the SDB mode is more realizable. In fact, the smaller viscosity ($\mu = 0.738 \text{ cP}$ case) gives the narrow $U/V$ range where the two-valueness is observed as illustrated in figure 11. Although the feasibility of the breakup length in the laminar SDB mode is described as above, the two-valueness is not fully explained yet. One of the possibilities is that a slight difference in the start conditions of the liquid injection can affect the velocity distribution inside and eventually outside of the nozzle. The energy transferred from the liquid tip to the nozzle exit through the capillary waves propagating upstream is comparatively large [6]. Since capillary waves with larger wavelength have larger amplitude due to their dispersive nature, the energy disturbing the liquid flow inside of the nozzle is larger at the beginning of liquid injection than that at the quasi-steady breakup state. There is a possibility that such large energy affects separation bubbles at the entrance of the nozzle parts and their change can lead to more uniform velocity distribution at the nozzle exit than that of the LDB mode. Put another way, the ‘coupling’ of the internal and the external flow fields can cause the laminar SDB mode. If the energy sufficient enough to affect the flow inside of the nozzle is not transferred to the nozzle exit at the beginning of injection, the velocity distribution would be dominated only by viscosity inside of the nozzle and the LDB mode appears. However, the laminar SDB mode case was not observed. The detailed condition for the realization of the laminar SDB mode has not been clear yet. In order to validate and control the realization of the two-valueness, a lot of experiments in the same condition are necessary.

![Figure 11. Two-valueness of breakup length on a certain liquid issue speed. The results for a nozzle of $a = 1.03\text{mm}$ is emphasized in this figure. Symbols corresponding to other experimental conditions are the same as ones in figure 11. LDB and SDB correspond to long distance breakup and short distance breakup, respectively.](image1)

![Figure 12. Typical images indicating two-valueness of breakup length.](image2)
5. Experiments on ISS

As noted above, gravity affects the generation of the unstable waves through acceleration of liquid issuing from a nozzle. In addition to the destabilization of the capillary wave, the unstable wave cannot keep its wavelength during its convection. These effects appear dominantly in the small $U/V$ case. In addition, it is predicted that the length of the relaxation region becomes smaller due to the gravity in the small $U/V$ and large $Bo$ cases. Since our new breakup theory must be examined through experimental results, it is desirable to remove what affects the breakup configuration, gravity in this case. The best solution is the microgravity experiments. However, the limitation to the number of experiments has prevented from obtaining the sufficient number of the microgravity experimental results and then the repeatability has not fully confirmed yet. In particular, the existence of two-valueness has only been confirmed only on the normal gravity condition and must be also examined on the microgravity environment through multiple experiments.

Several experiments are projected where the liquid issue speed is changed through several stages as illustrated in figure 13. Initial $U/V$ is approximately 1.10 for all of the experiments. Before obtaining the maximum liquid issue speed $(U/V)_{\text{max}}$, the liquid issue speed is increased through 20 phases by an interval of $\Delta(U/V) = (U/V)_{\text{max}}/20$. Since then the liquid issue speed is decreased by $\Delta(U/V) = (U/V)_{\text{max}}/10$ through 10 phases. In order to distinguish several types of experiments clearly, such experiments and the ones described in section 4 are named as the continuous and the single injection experiments, respectively. On the basis of the previous experiments, the time interval of a certain constant liquid issue speed is determined as approximately 4 s. The total experimental time amounts to approximately 120 s. Since all of the images from the beginning to the end of the liquid injection are unable to be obtained due to the limitation of memories installed on a high-speed camera, the images corresponding to approximately 50 breakups after reaching the steady liquid issue speed are realized for every $U/V$. Such long-period experiments are realizable only on ISS. High-speed ($(U/V)_{\text{max}} = (U/V)_{\text{cr}}$, in section 4) and low-speed ($(U/V)_{\text{max}} = 2$) experiments are projected. The low-speed case includes the region where the breakup length is dominated by the short-wave mode which is peculiar to microgravity environment ($U/V < 1.58$). The breakup in the short-wave mode is affected by the large-amplitude capillary waves reflected at the nozzle exit. Therefore, around the nozzle exit the strong interference of the capillary waves can be observed in detail and the waves formed on the liquid surface can differ from those for the single injection experiments. It follows that the low-speed continuous injection experiments are suitable to investigate the effects of the time histories of capillary waves. In the high-speed continuous injection case, along with effects of the time histories, the two-valueness of the breakup length can be examined. There is a possibility that even on the experimental conditions where both SDB and LDB are observed in the single injection experiments, SDB only realizes in the continuous ones. In addition, by the use of the nozzles of the several radii and lengths, the effects of nozzle will be examined.

Furthermore, the experiments aimed at obtaining the correlation functions for the time histories of the liquid tip location are planned. As noted above, the capillary waves emanated from the liquid tip

![Figure 13. A schematic of representative microgravity experiments on ISS.](image-url)
have the roles of upstream energy transfer and generation of the resulting unstable waves at the nozzle exit. The correlation of the time histories of the liquid tip can give the information related to the wave structures. The small $U/V$ cases ($< 2.0$) are targets of this kind of experiments. Since the waves at nozzle exit can be comparatively visible in the small $U/V$ case, the statistic characteristics obtained through the time histories of the breakup length can be examined by the use of the information of waves around the nozzle exit. Concretely, the images including several times breakups are taken at the specified time intervals during a long-period and single injection experiment.

As noted above, almost all of our experimental setup can be directly applied to the experiments on ISS. There is a possibility that the droplets scattering from the base part of the test section prevents from obtaining images of liquid jet during such long-period microgravity experiments. One of solutions for such a problem is the use of sponge blocks with high water-absorption performance. Considering the necessity to reduce experimental instruments and to avoid excess procedures, automatic water-absorption by sponge blocks can be one candidate. The behavior of the scattering droplets and water-absorption performance of sponge blocks were investigated through microgravity experiments by the use of parabolic flights. PVA sponge blocks made by AION with approximately 80 $\mu$m pores were adopted and installed at the bottom of the test section. Typical figures around the sponge block are shown in figure 14. Large droplets scattering from the blocks were not observed. The images obtained approximately 16 s after the beginning of liquid injection are shown in figure 15. Vitiation due to the fine droplets near the base part is observed only in the high-speed injection case. Such contamination of the test section can be avoided by making a hole on the sponge block. Water-absorption capacity of PVA sponge block during the long-period experiments was confirmed through other normalgravity experiments. Of course, other methods can be used for collection of water and

![Figure 14](image)

**Figure 14.** Typical successive images around surface of a sponge block located at the bottom of the test section.

![Figure 15](image)

**Figure 15.** Images indicating scattering of fine droplets from a sponge block.
final solution is currently under consideration.

6. Conclusion
Breakup process of a liquid jet issued from a circular nozzle, which has been attributed to ‘some kind of disturbance existing in nature and inside of a nozzle’, has been investigated through a new breakup theory. The spontaneous breakup occurs by the short-wave mode as long as the tip of the liquid jet exists. The steady breakup length is determined only by the short-wave mode if the case of \( U/V < 1.58 \). If \( U/V \) exceeds 1.58, the breakup by the short-wave mode cannot fix the breakup length and the unstable waves have important roles for the realization of the steady breakup length. Even in such a case, the main determinant for the liquid breakup is the capillary waves emanated from the liquid tip after each breakup. The reproduction and the reflection of the capillary waves at the nozzle exit can generate the unstable waves with the same amplitude as that of the capillary waves. A self-closed breakup cycle is established by the wave structures. From normalgravity experiments, it was found that the breakup length is classified into the LDB and the SDB modes. The breakup length in the LDB mode is occupied by the long relaxation region. While the separation bubbles or turbulence formed inside of the nozzle causes the turbulent SDB mode, the uniform velocity distribution due to the coupling of the flow fields inside and outside the nozzle is thought to be necessary for the realization of the laminar SDB mode. Although gravitational acceleration is inherently negligible for turbulent atomization, it can generate the unstable waves from the capillary waves and change the length of the relaxation region in normalgravity experiments. This is why microgravity experiments are desirable for establishing a comprehensive breakup theory. In addition, the effect of time histories of the waves on the breakup of liquid jet and the appearance of the two-valueness of the breakup length is suggested from our breakup theory. In order to investigate such unclear points, the microgravity experiments on ISS which can provide long-period microgravity environments are currently projected. The experimental setup of our previous experiments is directly applicable to such experiments and thus the high feasibility of such experiments is expected.

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