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# Effects of Orifice Internal Flow on Breakup Characteristics of Like-Doublet Injectors

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**Under cold-flow and atmospheric ambient pressure conditions, the breakup characteristics of liquid sheets formed by a like-doublet injector were investigated. The sheet breakup wavelength, which induces the sheet to be broken into ligaments, and the sheet breakup length, which is important for finding the flame location, were measured using stroboscopic light. After sheet breakup, liquid ligaments are formed intermittently, and their wavelengths are believed to be related to the combustion instability of liquid-rocket engine. Therefore, the wavelength and the breakup length of ligaments broken into fine drops were also measured. Because these spray characteristics are affected by the flow characteristics of the two liquid jets before they impinge on each other, the focus was on the effects of orifice internal flow, such as the cavitation phenomenon that occurs inside a sharp-edged orifice. From the experimental results, it was found that liquid jet turbulence delays sheet breakup and shortens the wavelengths of both sheets and ligaments. Because the turbulence strength of a sharp-edged orifice is stronger than that of a round-edged orifice, the shape of orifice entrance gives large differences in the spray characteristics. With these results, empirical models of the spray characteristics of a like-doublet injector were proposed, and these models can provide useful and practical data for use in designing liquid-rocket combustors.**

## Nomenclature

$C_d$ = orifice discharge coefficient
$d_j$ = jet diameter
$d_o$ = orifice diameter
$f_{b,l}$ = breakup frequency of liquid ligament, $U_l/\lambda_{b,l}$
$f_{b,s}$ = breakup frequency of liquid sheet, $U_s/\lambda_{b,s}$
$Oh$ = Ohnesorge number, $\mu/(\rho_l \sigma d_o)^{0.5}$
$P_B$ = ambient back pressure
$P_l$ = total pressure in orifice chamber
$P_v$ = liquid vapor pressure, 0.0234 and 0.0024 bar for water and kerosene, respectively
$Re_j$ = Reynolds number of liquid jet, $\rho_l U_j d_o/\mu$
$t_{b,l}$ = breakup time of liquid ligament, $x_{b,l}/U_l$
$t_{b,s}$ = breakup time of liquid sheet, $x_{b,s}/U_s$
$U$ = velocity
$We_j$ = Weber number of liquid jet, $\rho_l U_j^2 d_o/\sigma$
$x_{b,l}$ = breakup length of liquid ligament, distance from sheet edge to drops
$x_{b,s}$ = breakup length of liquid sheet, distance from impingement point to sheet edge
$\Delta P$ = injection pressure, $P_1 - P_B$
$\theta$ = half impingement angle, half-angle between two liquid jets
$\lambda_{b,l}$ = breakup wavelength of liquid ligament, distance from sheet edge to first ligament
$\lambda_{b,s}$ = breakup wavelength of liquid sheet, distance from last wave inside sheet to sheet edge
$\mu$ = liquid viscosity, 0.0085 and 0.016 g/cm · s for water and kerosene, respectively
$\rho_g$ = ambient gas density
$\rho_l$ = liquid density, 1.0 and 0.8 g/cm$^3$ for water and kerosene, respectively
$\sigma$ = surface tension, 72 and 26 g/s$^2$ for water and kerosene, respectively

*Subscripts*

$j$ = liquid jet
$l$ = liquid ligament
$s$ = liquid sheet

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## I. Introduction

LIKE-DOUBLET injectors that atomize liquid mass into fine drops using the impinging momentum of two liquid jets are commonly used in liquid-rocket engines because they offer low manufacturing cost, potentially high flow rate, compatibility to the chamber wall, and so forth.[1] Therefore, the spray formed by the injector has been studied extensively. Taylor[2] analytically modeled the shape and thickness of a liquid sheet formed by water jets and compared the results with his experimental data. Whereas his theory was restricted to the conditions of very low injection velocity, Dombrowski and Hooper[3] found that waves are formed on the liquid sheet by the impact force of the two liquid jets and that the characteristics of spray atomization are determined by the growth and breakup of these waves at higher velocity conditions. According to this breakup mechanism, the spray patterns from like-doublet injectors show periodic breakup due to the impact wave. Heidmann et al.[4] measured the breakup frequency by using a photoelectric method that detects the intensity fluctuation of the light passing through the spray. Anderson et al.[5] also focused on the breakup periodicity and presented its relations to the combustion instability of a liquid-rocket engine by comparing the breakup frequency of the sheet with the instability frequencies of practical rocket combustors. However, their experimental results do not agree well with analytical models, and, thus, there have not been reliable models that can analyze the breakup characteristics of liquid sheets.[5] One of the most important reasons for this lack of agreement in results is that various orifices that are different with respect to their material, inner surface roughness, treatment quality of orifice hole, and so forth have been used. These different orifices may have resulted in conflicting data that show differences in the flow characteristics in liquid jets. Because the laminar or turbulent characteristics of a liquid jet dominate the breakup mechanism of a liquid sheet[3] and the turbulence strength of a liquid jet is strongly affected by the internal flow in the orifice, the inner condition of the orifice is believed to be very important in determining the spray characteristics of a like-doublet injector.

Cavitation greatly affects the steady internal flow in the orifice.[6–8] An abrupt change in the flow direction at the entrance of the orifice reduces the local static pressure up to the saturation pressure, at which point cavitation bubbles appear at the entrance. These bubbles cause turbulence in the internal flow, and, thus, jet characteristics become dependent on the flow time, which implies unsteady flow. When the cavitation bubbles develop, they can induce the liquid flow to separate from the orifice wall. This hydraulic flip phenomenon reduces the mass flow rate of propellant and causes the misimpingement of the impinging-type injectors. Although the flip seldom occurs in the high ambient pressure of liquid-rocket combustors, the cavitation still inside the orifice produces turbulent jet flow.[7]

Tamaki et al.[8] studied the turbulence characteristics of sharp- or round-edged orifice jets for a diesel engine and measured the jet breakup lengths. As for liquid-rocket injectors, Nurick[6] reported that, based on the cold-flow test he conducted, the cavitation reduces the mixing efficiency of the unlike-doublet injector. However, the cavitation effects on the spray characteristics of liquid sheets formed by like-doublet injectors have not been reported.

In this paper, we show internal flows of sharp- or round-edged orifices and investigate their effects on the breakup characteristics of liquid sheets. The final objective of this study was to obtain empirical models on the breakup lengths and the breakup wavelengths or frequencies of sheets or ligaments for practical like-doublet injectors. Therefore, we propose models for the sharp-edged orifice that are more commonly used in practical systems as functions of the Weber number, impingement angle, and liquid properties.

## II. Experimental Method

We designed both sharp- and round-edged orifices for like-doublet injectors as shown in Fig. 1. According to Vennard's experimental results,[9] an orifice with an entrance that is rounded to 0.14 times the orifice diameter or more has no a vena contracta. To make noncavitation flow, a round-edged orifice was designed with a curvature radius as one diameter of the orifice. In this case, the

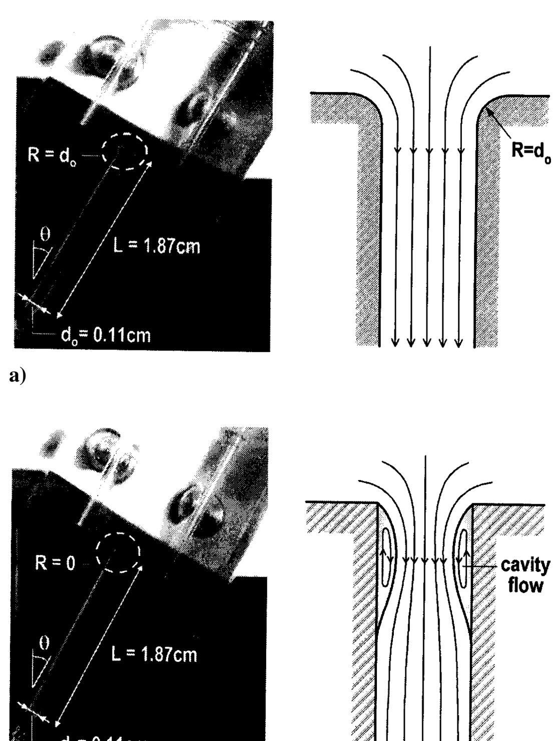



**Fig. 1 Orifice design and schematics of internal flow: a) round-edged orifice and b) sharp-edged orifice.**

**Table 1 Dimensions of orifice design parameters**

| Orifice design parameters | Dimensions |
|---|---|
| Orifice entrance shape | Round ($R = 1d_o$), sharp ($R = 0$) |
| Orifice diameter $d_o$, cm | 0.11 |
| Preimpingement length of liquid jet, cm | 0.55 (=$5d_o$) |
| Ratio of orfice length to diameter | 17 |

**Table 2 Dimensions of experimental conditions**

| Experimental conditions | Ranges |
|---|---|
| Fuel simulant | Water, kerosene |
| Impingement angle $2\theta$, deg | 50, 60, 70, 80, 90 |
| Injection pressure $\Delta P$, bar | 1, 2, 3, 4, 5, 6 |
| Jet Injection velocity $U_j$, cm/s | 950 ~ 3000 |

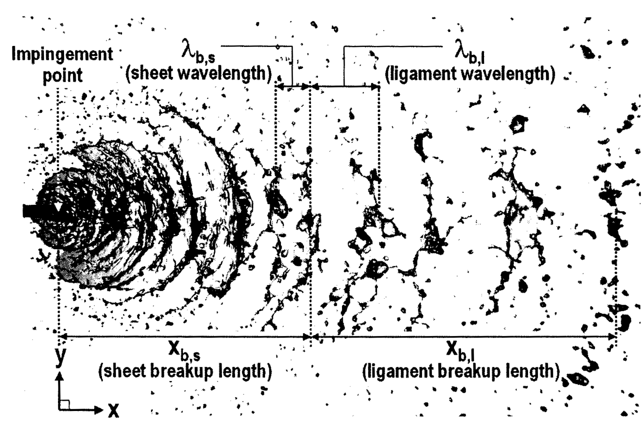



**Fig. 2 Breakup pattern of liquid sheet formed by like-doublet injector and definitions of breakup characteristic parameters.**

internal flow in a round-edged orifice is so smooth that it has no perturbation, as shown in the schematic of Fig. 1a (Ref. 8). Unlike a round-edged orifice, the internal flow in a sharp-edged orifice has to change its direction rapidly at the orifice entrance, and so a cavity flow is formed (Fig. 1b). If the static pressure of the cavity is lower than the saturation pressure, the cavitation occurs in the cavity. In addition, because the flow changes direction as it passes or enters the orifice, the flow becomes turbulent, and this is especially true for short orifices. According to Dombrowski and Hooper,[3] the ratio of orifice length to diameter has to be greater than 400 to obtain a fully developed flow. Because our orifices were too short and, thus, could not stabilize the turbulence of the internal flow, the sharp-edged orifice in Fig. 1b is believed to have formed a turbulent jet.

Table 1 shows the dimensions of the orifice design parameters, and Table 2 shows the dimensions of the experimental conditions. The orifice diameter was 0.11 cm and the ratio of the orifice length to diameter was designed to be 17, which is greater than those of practical like-doublet injectors, to induce steadier flow. The impingement point of the two liquid jets was fixed at a location that was five times the orifice diameter from the orifice exit. The injection pressure was varied from 1 to 6 bars, and the impingement angle, which indicates the angle between two orifices, was varied from 50 to 90 deg. The injection velocities of liquid jets were controlled from 950 to 3000 cm/s by varying the injection pressure. According to Kline et al.,[10] the periodicity of the sheet breakup disappears when the injection velocity is greater than 3000 cm/s because the liquid jets are atomized before the impingement. Because the present injection velocities were not greater than 3000 cm/s, the breakup wavelengths could be measured for all of the experimental conditions.

As shown in Fig. 2, the atomization process of a unielement like-doublet injector consists of the formation of the liquid sheet, the fragmentation of the liquid sheets into ligaments, and the ligament breakup into fine drops. The spray produced by this injector has two characteristics: its periodic breakup pattern and the almost two-dimensional plane distribution of the drops. This type of distribution results because the impact wave on the liquid sheet determines the breakup of the sheet.[3] The liquid jet and sheet can be laminar if the injection velocity is low and there is no perturbation on the passage. In this case, the aerodynamic force between the liquid sheet and ambient gas becomes more important than the impact force of the two liquid jets. However, turbulent flow is more common because the injection pressure is very high and the injector orifice is not smooth in rocket engines.[1] Therefore, we focused on the turbulent liquid sheets formed by the turbulent liquid jets.

The breakup length of a liquid sheet $x_{b,s}$ was defined as the distance from the impingement point to the edge of liquid sheet along the $x$ axis, as shown in Fig. 2. The breakup length of a ligament $x_{b,l}$ was defined as the distance from the edge of liquid sheet to the first group of drops. The ligaments are broken into fine drops by the aerodynamic force between the ligament and ambient gas.

The wavelength of the liquid sheet at the moment of the breakup of liquid sheet $\lambda_{b,s}$ is important for validating the linear instability theory, which states that there is a specific wavelength that induces the breakup of the liquid sheet.[11] The ligaments formed from the breakup of the sheet also have periodicity, and their wavelengths are believed to be related to combustion instability of liquid-rocket engines.[5] As shown in Fig. 2, the wavelength of a liquid ligament right after the breakup of the sheet may be larger than the breakup wavelength of the liquid sheet because the ligament loses the restriction forces of the liquid sheet, such as surface tension and viscosity, when it is released from the sheet. Therefore, we also defined the distance between the edge of the liquid sheet and the first ligament at the moment of sheet breakup as the breakup wavelength of the ligament $\lambda_{b,l}$. If the wavelengths are empirically modeled, the breakup frequency of the sheet or the ligament can be calculated by dividing the velocity of the sheet or ligament by its wavelength.

Heidmann et al.[4] also measured the frequency of the liquid ligament at a location where the intervals among the ligaments are distinct. However, the distances between adjacent ligaments were not constant along the $x$ axis, as shown in Fig. 2; the breakup frequency of the ligament depended on the location of the measurement. Hence, the criterion of the measurement location is crucial for determining the ligament frequency more consistently. In addition, the wavelength of the first ligament may be the most important because the ligament is rapidly vaporized downstream of the injector. Therefore, we measured the ligament frequency at the location where the sheet starts to breakup, and, thus, the measurement point is not fixed but is dependent on the breakup length of the liquid sheet.

## III. Flow Characteristics of Liquid Jets

Figure 3 shows discharge coefficients $C_d$ for round- and sharp-edged orifices. The discharge coefficient of a round-edged orifice was higher than that of sharp-edged orifice. The discharge coefficient of a sharp-edged orifice decreased as the injection pressure increased after about 2.5 bar (250 kPa). Nurick[6] found that the discharge coefficient of a sharp-edged orifice for the cavitation flow is determined by the following equation:

$$C_d = 0.62[(P_l - P_v)/(P_l - P_B)]^{0.5} \quad (1)$$

Because the discharge coefficient of the sharp-edged orifice in our experiment followed the preceding equation after 2.5 bars, we expected cavitation flow inside the orifice.

The orifice internal flow can be separated from the orifice wall after the cavitation bubbles are fully developed inside the orifice. This hydraulic flip phenomenon is very important for impinging-type injectors because it can cause the misimpingement of liquid jets.[7] According to Nurick,[6] the flip can be predicted from the discharge coefficient curve; the coefficient departs from Eq. (1) and has a constant value that is lower than the coefficient of the cavitation flow. However, under the present experimental conditions, the sharp-edged orifice did not show the flip because the orifice length was long enough for the separated flows to reattach.

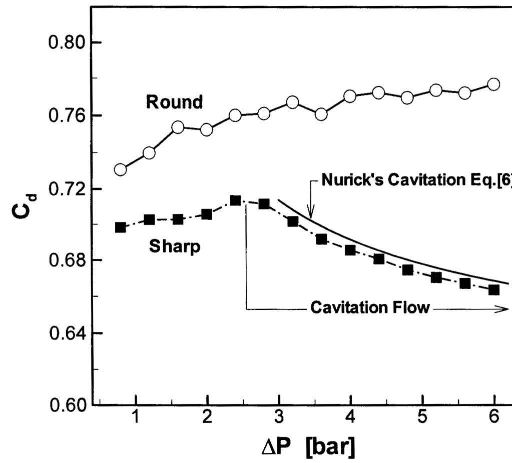



**Fig. 3 Discharge coefficients of round- and sharp-edged orifices as function of injection pressure.**

Figure 4 shows the shapes of orifice internal flows and jet flows for water and kerosene simulants as a function of injection velocity, which is the most important parameter for characterizing a liquid jet.[12] The injection velocities were calculated from the following equation[6]:

$$U_j = C_d(2\Delta P/\rho_l)^{0.5} \quad (2)$$

Because the discharge coefficients of round- and sharp-edged orifices as well as the liquid densities of water and kerosene simulants were not same, the injection pressures of the orifices were determined by using Eq. (2) for the same jet velocities in each case.

Figure 4a shows no significant differences in the internal or external water flow, regardless of the shape of the orifice entrance, when the jet velocity is 980 cm/s. At a higher velocity ($U_j = 1690$ cm/s, however, cavitation occurred inside only the sharp-edged orifice. (The cavitation bubbles are shown as white images in the internal flow photographs.) The jet flow images show that the cavitation bubbles cause the liquid jet to become turbulent. When the flow velocity was 2180 cm/s, the cavitation bubbles were fully developed inside the sharp-edged orifice, and, thus, the turbulence strength of the liquid jet increased. The turbulence strength of jet flow in the round-edged orifice, however, did not increase as much as that of the sharp-edged orifice.

Figure 4b shows that the turbulence strengths of kerosene jets were higher than those of water jets for the sharp-edged orifices under the same injection velocity. The reason may be that the surface tension force of kerosene is lower than that of water, so that the jet spreads rapidly at the exit of the orifice. In the case of a round-edged orifice, a laminar jet is formed for a low injection velocity, 980 cm/s. At a higher injection velocity ($U_j = 1690$ cm/s), the jet becomes semiturbulent; it has both the turbulent core and laminar envelope as Lefebvre mentioned (see Ref. 12). According to Dombrowski and Hooper,[3] the orifice can have a laminar liquid jet until the Reynolds number reaches $1.2 \times 10^4$ only if its entrance is very smooth. Therefore, as shown in Fig. 4a, all of the liquid jets of the round-edged orifices were turbulent because their Reynolds numbers were higher than $1.2 \times 10^4$.

To compare the turbulence strengths of liquid jets, we measured the diameters of liquid jets at the impingement location using 100 instantaneous images, and Fig. 5 shows the results. Although the jet diameter may not be an exact indicator of jet turbulence strength because it is based on not the internal jet structure but the outer jet shape, it can give qualitative information on the turbulence strength. As shown in Fig. 5, although the diameter of the water jet from a round-edged orifice increases just slightly as the Weber number

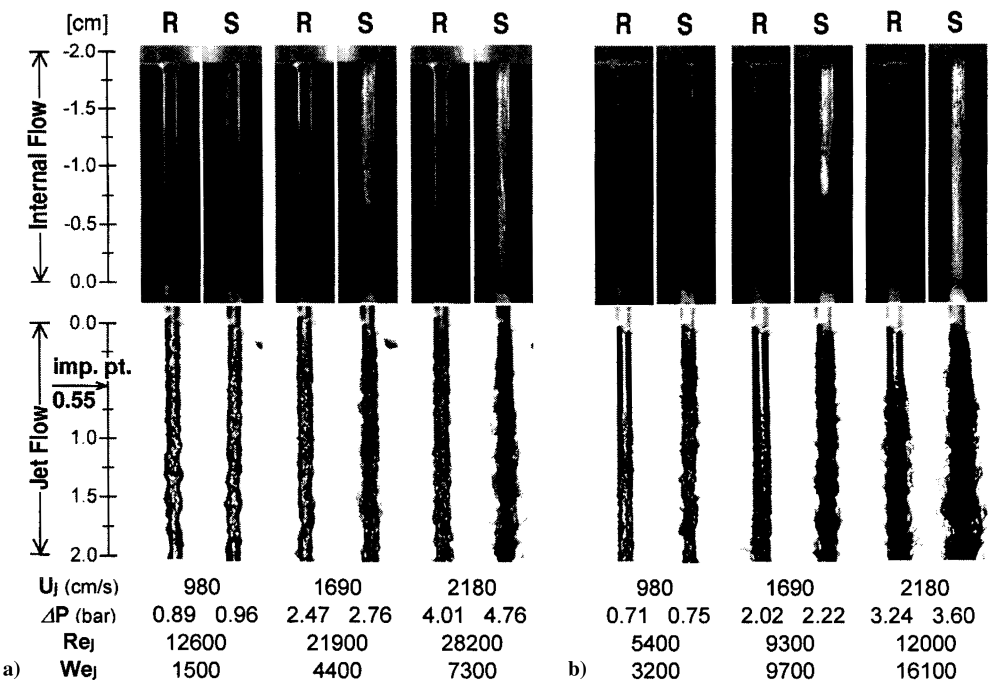



**Fig. 4 Internal flow and liquid jets for round- and sharp-edged orifices as function of injection velocity: a) water simulant and b) kerosene simulant.**

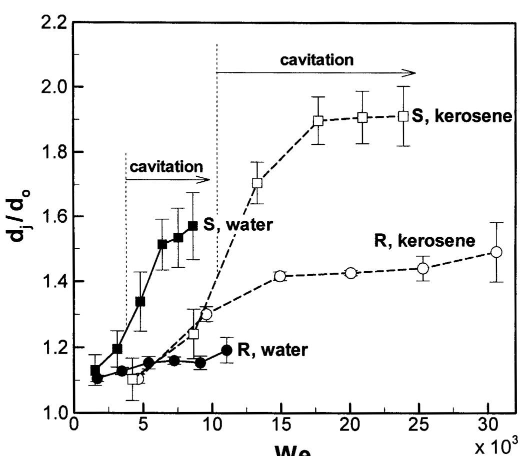



**Fig. 5 Single jet diameter at impingement point as function of Weber number of jet.**

increases, that of a sharp-edged orifice shows an S-curve, which implies that the diameter of the water jet increases rapidly when cavitation occurs inside the sharp-edged orifice and increases slowly after the cavitation is fully developed. The kerosene jet diameter for a sharp-edged orifice also showed similar trends as the water jet diameter for sharp-edged orifice, except for the higher increasing rate. As for the kerosene jet of a round-edged orifice, the rate of increase of the jet diameter was much higher than that of the water jet diameter of a round-edged orifice because the jet characteristics change rapidly from laminar to semiturbulent or fully turbulent.

From Figs. 4 and 5, the breakup characteristics of liquid sheets formed by the sharp-edged orifices are expected to be different from those of the round-edged orifices, even though the Weber number, which is known as the dominant parameter for the breakup mechanism of liquid sheets, was the same for both types of orifices. Because the cavitation of internal flow affects significantly the structure of the liquid jet at the location of the impingement point, the condition of the internal flow plays an important role in the spray characteristics of impinging-type injectors.

## IV. Breakup Lengths of Sheet and Ligament

We measured the breakup lengths of the liquid sheet and ligament, which were shown in the instantaneous spray images obtained by stroboscopic light. To confirm the reliability of the data, we analyzed 100 images for one experimental case and found that the deviations of that data were less than 10% from their mean values.

Figure 6a shows the breakup length of the liquid sheet $x_{b,s}$ as a function of the jet Weber number. First, the breakup lengths decreases regardless of the orifice entrance shape or the kind of simulant as the Weber number increases. The sheet breakup length can be expected to increase because the sheet velocity also increases as the Weber number increases. However, Fig. 6a shows opposite results to this expectation, and, thus, it is thought that the effect of the impact force of the two liquid jets predominates the sheet breakup rather than that of the sheet velocity.

For water sheets, as shown in Fig. 6a, the breakup length of the round-edged orifice (filled circles) is much larger than that of a sharp-edged orifice (filled square) when the Weber numbers for both orifices are about 1500, although both jet diameters are similar to those shown in Figs. 4 and 5. According to Dombrowski and Hooper,[3] the impact waves formed by the impingement of two liquid jets are diminished by the boundary flow of the jets. Because the boundary flow becomes thin as the turbulence strength of the jet increases, the liquid sheet is easily broken by the impact waves. Therefore, a jet's inner turbulence for a sharp-edged orifice is higher than that for a round-edged orifice, although both jets' outer shapes are similar. Consequently, it can be deduced that the shape of an orifice entrance has a crucial role in the breakup of a liquid sheet.

However, the water sheet breakup lengths between a round- and sharp-edged orifices become similar as the Weber number increases because the decrease rate of the water sheet breakup length of a sharp-edged orifice (proportional to $We_j^{-0.27}$) is lower than that of a round-edged orifice ($We_j^{-0.40}$) as shown in Fig. 6a. The similar breakup lengths may be due to the increase of jet turbulence by the cavitation. For sharp-edged orifices, the jet turbulence strength, as well as the impact force of the two jets, increases as the Weber number increases, and the jet turbulence may relax the effect of the impact force on the sheet breakup. Therefore, the Weber number effect on the sheet breakup length for a sharp-edged orifice is

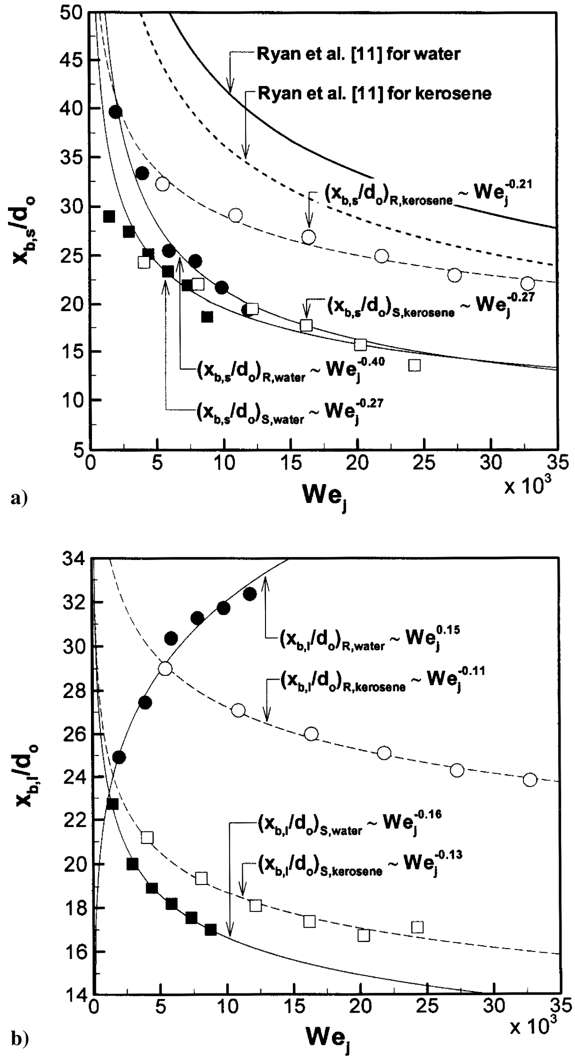



**Fig. 6 Breakup lengths of liquid sheet $x_{b,s}$ and ligament $x_{b,l}$ as function of Weber number of jet; $\theta = 30$ deg and $R$ and $S$ indicate round- and sharp-edged orifices, respectively: a) sheet breakup length and b) ligament breakup length.**

lower than that for a round-edged orifice, whose jet turbulence effect is not significant. In addition, because the turbulence strengths of kerosene jets for both round- and sharp-edged orifices also increase sensitively with the increase of Weber number as shown in Fig. 5, the sheet breakup lengths for both orifices show similar trends ($We_j^{-0.21}$ and $We_j^{-0.27}$ for round- and sharp-edged orifices, respectively) with the water sheet breakup length of the sharp-edged orifice.

As for the breakup length of a liquid sheet, Huang[13] obtained a semi-empirical relation by using a vibrating membrane model as follows:

$$x_{b,s}/d_o = 7.1(\rho_g/\rho_l)^{-\frac{2}{3}} We_j^{-\frac{1}{3}} \tag{3}$$

when the Weber number is greater than 2000. Because he used perpendicularly impinging jets, he did not consider the effect of the impingement angle. Ryan et al.[11] also suggested a breakup length model of a like-doublet injector based on the aerodynamic instability theories of Dombrowski and Hooper[14] and Hasson and Peck[15] as follows:

$$\frac{x_{b,s}}{d_o} = 5.451\left(\frac{\rho_g}{\rho_l}\right)^{-\frac{2}{3}} [We_j f(\theta)]^{-\frac{1}{3}}$$

$$f(\theta) = \frac{(1-\cos\theta)^2}{\sin^3\theta} \tag{4}$$

Because both breakup length models are basically based on the aerodynamic instability theory, the powers of the Weber number or the density ratio of gas to liquid are the same in Eqs. (3) and (4).

The model by Ryan et al.[11] shows a similar trend with the present experimental data as shown in Fig. 6a, although their model overestimated the breakup length quantitatively. However, their model predicts that the breakup length of kerosene (dashed line) is smaller than that of water sheet (solid line), which is contrary to the present results. According to the linear instability theory based on the balance between surface tension force and aerodynamic force, because the amplitude of the sheet wave increases as the liquid density decreases, the liquid sheet of kerosene whose density is smaller than that of water is broken early. In the breakup of the present turbulent sheet, however, the impact force of two liquid jets is more important than the aerodynamic force.[3] Because the impact forces of both kerosene and water jets are the same at the same Weber number, the sheet breakup lengths of both jets are determined by the turbulence strength of jets, as we mentioned. Therefore, the breakup length of a kerosene sheet becomes larger than that of a water sheet at the same Weber number because the turbulence strength of a kerosene jet is stronger than that of a water jet, as shown in Figs. 4 and 5.

Figure 6b shows the breakup length of the liquid ligament $x_{b,l}$, which is defined as the distance for the liquid ligament to be broken into fine drops. Whereas the water ligament breakup length for a sharp-edged orifice (filled squares) decreases as the Weber number increases, that is, increases in proportion to $We_j^{-0.16}$, that for a round-edged orifice (filled circles) increases in proportion to $We_j^{0.15}$. This difference is important in understanding the mechanism of ligament breakup. According to Dombrowski and Hooper,[3] the velocities of the sheet $U_s$ or ligament $U_l$ maintain the injection velocity of the jet $U_j$ because there is no dissipation mechanism when the jet changes into the sheet or ligament. Therefore, as the Weber number of the jet, $\rho_l U_j^2 d_o/\sigma$, increases, the velocity of the ligament also increases. The increase in the ligament velocity may result in two contradicting phenomena for the breakup length of ligament: a long penetration distance due to the increase in the velocity itself and a short breakup length due to the increase in the aerodynamic drag force. However, the aerodynamic drag force is not significant when the relative velocity between the jet and the surrounding gas is comparable to the jet velocity, as in present experiment.[16,17] Therefore, the breakup length of the water ligament of a round-edged orifice, which is closely related to the penetration length of the ligament, increases as the Weber number increases.

Unlike the water ligament breakup length of a round-edged orifice, the water ligament breakup length of a sharp-edged orifice (filled squares) and the kerosene ligament breakup lengths of both round- (open circles) and sharp-edged orifices (open squares) decrease at a rate similar to the rate of increase of the Weber number. This may be explained by the turbulent characteristics of jets; because the structures of a liquid ligament may become weak as the turbulence strength increases, the turbulence effect becomes more dominant than the effect of increasing penetration distance. In the foregoing three cases, therefore, the breakup lengths of ligaments decrease as the Weber number increases. In contrast, because the turbulence strengths of water jets of round-edged orifices do not increase greatly as shown in Figs. 5 and 6, the effect of ligament penetration distance may become more important than the turbulence effect, and, thus, the breakup length of the water ligament increases, as mentioned.

To identify the effects of the impingement angle on the breakup of a sheet or ligament, we measured the breakup lengths of the sheet and ligament as a function of the impingement angle at the fixed Weber number of 5900. Although the impact force of two liquid jets is proportional to the square of the sine of one-half of the impingement angle $\theta^3$, the turbulence strength of a jet may not be changed significantly because the Weber number is fixed. Therefore, Fig. 7 shows the effect of the impact force on the breakup characteristics without consideration of the effect of the jet turbulence strength.

Figure 7 shows that the water sheet breakup lengths of both the round- (filled circles) and sharp-edged orifices (filled squares) are proportional to $(\sin^2\theta)^{-0.60}$, although they are proportional to

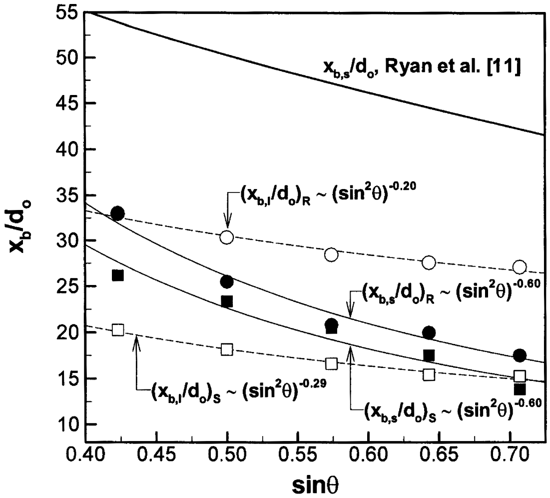



**Fig. 7 Breakup lengths of liquid sheet $x_{b,s}$ and ligament $x_{b,l}$ as function of sine of one-half of impingement angle (water simulant, $We_j = 5900$).**

$We_j^{-0.40}$ and $We_j^{-0.27}$, respectively, in Fig. 6a. If we assume that the impingement angle affects only the impact force whereas the Weber number affects the jet turbulence strength as well as the impact force, the differences in powers between $We_j$ and $\sin^2\theta$, that is, $-0.40-(-0.60) = +0.20$ for a round-edged orifice and $-0.27-(-0.60) = +0.33$ for a sharp-edged orifice, are thought to indicate how much effect the jet turbulence strength has on the breakup length. Because the jet turbulence increases the sheet breakup length by relaxing the impact force and the increase in turbulence strength of a round-edged orifice is lower than that of a sharp-edged orifice, the sheet breakup length of a round-edged orifice becomes more sensitive to the Weber number than that of a sharp-edged orifice.

Figure 7 also shows that the ligament breakup lengths of both the round (open circles) and sharp-edged orifices (open squares) decrease slightly as the impingement angle increases. From the decrease rates of the ligament breakup lengths being lower than those of the sheet breakup lengths, the ligament breakup was found to be less sensitive to the impact force than the sheet breakup is because the ligaments are farther from the impingement point.

Figures 6 and 7 show that the jet turbulence strength as well as the impact force of two liquid jets is important for both sheet and ligament breakup lengths. By using these experimental data, we could obtain empirical relations on the breakup lengths of a sheet and a ligament for the sharp-edged orifice as follows:

$$x_{b,s}/d_o = 97.3 We_j^{-0.27}(\sin\theta)^{-1.20} \tag{5}$$

$$x_{b,l}/d_o = 69.8 Oh^{0.094} We_j^{-0.14}(\sin\theta)^{-0.58} \tag{6}$$

where the Ohnesorge number, $\mu/(\rho_l \sigma d_o)^{0.5}$, was used to compensate for the quantitative difference between water and kerosene simulants with their properties such as density, viscosity, and surface tension.[12] Note that the sheet breakup length is not related to the Ohnesorge number, as shown in Eq. (5).

When the breakup lengths of Eqs. (5) or (6) are devided by the sheet or ligament velocities, the breakup times of the liquid sheet or ligament could be predicted as follows:

$$t_{b,s,\text{water}} = 0.42 We_j^{-0.77}(\sin\theta)^{-1.20}$$

$$t_{b,s,\text{kerosene}} = 0.62 We_j^{-0.77}(\sin\theta)^{-1.20} \tag{7}$$

$$t_{b,l,\text{water}} = 0.17 We_j^{-0.64}(\sin\theta)^{-0.58}$$

$$t_{b,l,\text{kerosene}} = 0.29 We_j^{-0.64}(\sin\theta)^{-0.58} \tag{8}$$

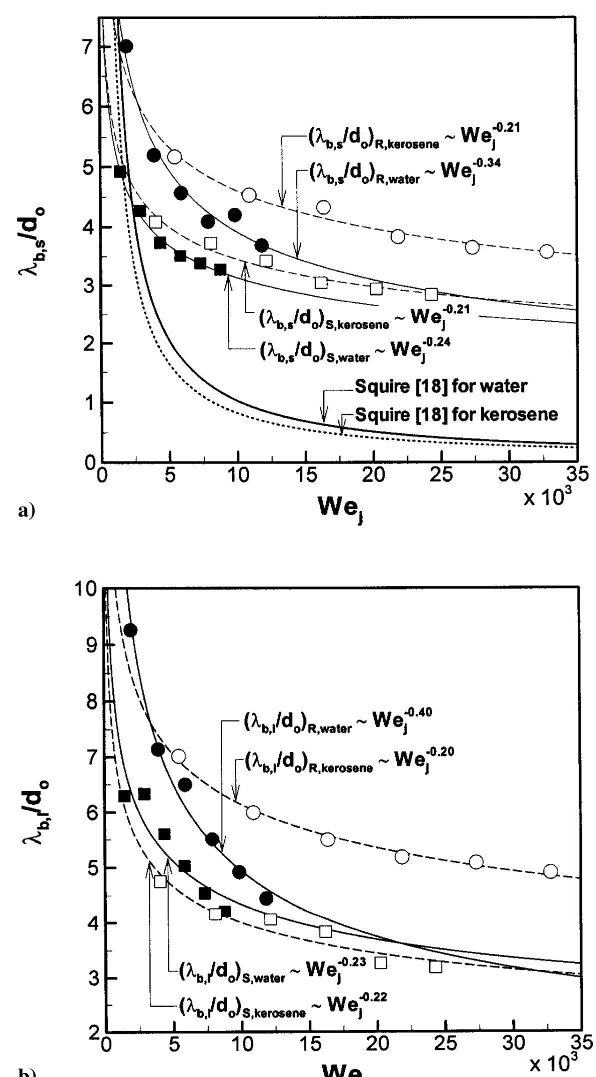
where the units of breakup times are seconds and the velocities of the sheet and ligament are assumed to be the same as the velocity of a liquid jet.[3] The preceding equation indicates that the sheet or ligament of a kerosene simulant may take longer to break up than that of a water simulant at the same Weber number and impingement angle (about 50 and 70% more for the sheet and ligament, respectively).

## V. Breakup Wavelengths of Sheet and Ligament

Squire[18] proposed the breakup wavelength that generates the highest amplitude of the liquid sheet by using the linear instability theory, as follows:

$$\lambda_{b,s}/d_o = 4\pi(\rho_g/\rho_l)^{-1} We_j^{-1} \tag{9}$$

However, the present experimental data in Fig. 8a show that this theory excessively overestimates the effects of the Weber number so that it underestimates the wavelength. In addition, the Squire's model predicts that the breakup wavelength of the kerosene sheet (dotted line) is shorter than that of water sheet (solid line) at the same Weber number, which is contrary to the present results. This difference between the results may be explained by the fact that Squire did not consider the impact force of liquid jets because his model is based on a flat expanding sheet injected from a rectangular slit hole. Consequently, Fig. 8a shows that the linear instability theory based on only the aerodynamic force without the impact force




a) b)

**Fig. 8 Breakup wavelengths of liquid sheet $\lambda_{b,s}$ and ligament $\lambda_{b,l}$ as function of Weber number of jet, $\theta = 30$ deg: a) sheet breakup wavelength and b) ligament breakup wavelength.**

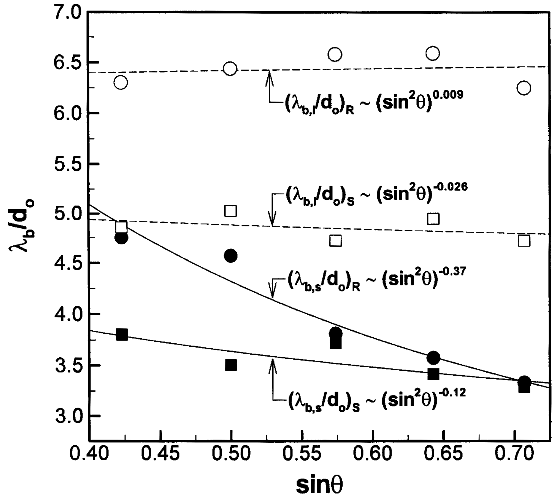



**Fig. 9 Breakup wavelengths of liquid sheet $\lambda_{b,s}$ and ligament $\lambda_{b,l}$ as function of sine of one-half of impingement angle (water simulant, $We_j = 5900$).**

or jet turbulence cannot predict the breakup characteristics of liquid sheets formed by like-doublet injectors.

Figure 8a also shows the similar trends with the sheet breakup lengths; the water sheet wavelength of the round-edged orifice (proportional to ($We_j^{-0.34}$) is more sensitive than the water sheet wavelength of a sharp-edged orifice ($We_j^{-0.24}$) and the kerosene sheet wavelengths of round- ($We_j^{-0.21}$) and sharp-edged orifices ($We_j^{-0.21}$). This greater sensitivity can be explained by the effects of the impact force and the jet turbulence strength. Figure 9 shows the effect of the impingement angle on the sheet or ligament wavelengths. The sheet wavelengths of round- and sharp-edged orifices are proportional to $(\sin^2\theta)^{-0.37}$ and $(\sin^2\theta)^{-0.12}$, respectively. Because the water jet turbulence strength of a round-edged orifice does not change significantly, the variation in the power of its sheet wavelength is not significant, that is, from $-0.37$ to $-0.34$. In contrast, because the turbulent jet may prevent the wave within the sheet from fully developing, the sheet wavelength of a sharp-edged orifice decreases as the Weber number increases so that the power varies greatly, that is, from $-0.12$ to $-0.24$; in other words, it is believed that the decrement of $-0.12$ results from the effect of the increase of jet turbulence strength.

The breakup wavelength of a ligament has as similar tendency as that of a sheet as shown in Fig. 8b, although the wavelength of a ligament is slightly larger than that of a sheet as we predicted from Fig. 2. The effects of orifice entrance shape and liquid properties on the ligament wavelength are very similar. Therefore, the ligament wavelength depends on the sheet wavelength. However, the breakup wavelength of a ligament was independent of the impingement angle, regardless of the shape of the orifice entrance, as shown in Fig. 9.

We obtained empirical relations on the breakup wavelengths of sheets and ligaments from the results of sharp-edged orifices of Figs. 8 and 9 as follows:

$$\lambda_{b,s}/d_o = 45.2\ Oh^{0.096} We_j^{-0.24} (\sin\theta)^{-0.24} \tag{10}$$

$$\lambda_{b,l}/d_o = 46.7\ Oh^{-0.078} We_j^{-0.23} \tag{11}$$

When Eq. (10) is compared with Squire's theory in Eqn. (9), the effect of Weber number is mitigated; the power of Weber number is changed from $-1$ to $-0.24$.

The breakup frequencies of a sheet or ligament could be obtained by dividing the velocities of the sheet or ligament with the breakup wavelengths of Eqs. (10) or (11). The velocities of the sheet and ligament were assumed again to be same as the injection velocity,[3]

$$f_{b,s,\text{water}} = 8.98 We_j^{0.76} (\sin\theta)^{0.24}$$

$$f_{b,s,\text{kerosene}} = 5.35 We_j^{0.76} (\sin\theta)^{0.24} \tag{12}$$

$$f_{b,l,\text{water}} = 3.17 We_j^{0.73}, \qquad f_{b,l,\text{kerosene}} = 2.35 We_j^{0.73} \tag{13}$$

where the units of breakup frequencies are the inverse of seconds, namely, hertz.

Whereas, Eq. (13) shows that the breakup frequency of a ligament is independent of the impingement angle, Heidmann[4] reported that the frequency is proportional to $\cos\theta$; in other words, the wavelength of the ligament increases as the impingement angle increases. This difference results from the uncertainty of Heidmann's measurement location. As the impingement angle increases, the breakup length decreases (Fig. 7) and the wavelength of the ligament increases along the $x$ axis after it is separated from the sheet (Fig. 2). As a result, the wavelength of the ligament can increase as the impingement angle increases if the measurement location is fixed.

## VI. Conclusions

From the experiments on the breakup lengths and wavelengths of liquid sheets and ligaments formed by a like-doublet injector, the following conclusions could be drawn:

1) The turbulence strength of each jet as well as the impact force of two jets is an important factor affecting the breakup characteristics of liquid sheets and ligaments. The turbulence strength of the jet is affected by the orifice entrance shape, injection velocity, liquid properties, and so on. In particular, the cavitation bubbles that occur inside the sharp-edged orifice at high Weber numbers make the liquid jet very turbulent.

2) Although the impact force decreases the breakup length of a liquid sheet, the liquid jet turbulence relaxes the effect of impact force on the liquid sheet. Therefore, the water sheet breakup length of a round-edged orifice is more sensitive to the Weber number than that of a sharp-edged orifice because the turbulence strength of the water sheet does not changed significantly as the Weber number increases.

3) The jet turbulence strength as well as the impact force reduces the sheet breakup wavelength because the jet turbulence prevents the wave within the sheet from fully developing. Therefore, the sheet wavelength of a sharp-edged orifice becomes more sensitive to the Weber number as the result of jet turbulence, but that of a round-edged orifice is determined by only the impact force because the jet turbulence strength of a round-edged orifice does not change significantly.

4) The surface tension force of kerosene is lower than that of water, so that the jet diameter spreads rapidly at the exit of the orifice. Therefore, the turbulence strength of a kerosene jet, regardless of the orifice entrance shape, shows a similar tendency with that of the water jet of a sharp-edged orifice. Consequently, the spray characteristics of the kerosene sheet show similar trends with those of the water sheet formed by the sharp-edged orifice.

5) As for the sharp-edged orifice, which is more practical than the round-edged orifice, the breakup length of a liquid sheet, which is important for determining the flame location, is proportional to $We_j^{-0.27}(\sin\theta)^{-1.20}$. In addition, the breakup wavelength of a ligament, which is believed to be related to the combustion instability of rocket combustor, is proportional to $Oh^{-0.078} We_j^{-0.23}$.

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