

Effect of Nozzle Length on Breakup Length of Liquid Jet

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Although the stability of Newtonian liquid jet has been investigated experimentally and theoretically, many problems has remained unsolved. Especially, the stability of liquid jets in immiscible liquid systems has been little studied. Furthermore, one has to point out that the stability of jets may be influenced by the turbulence in the nozzle and the velocity profile. This work presents the experimental result about the effect of the nozzle length on the breakup length of liquid jets in the air and in the immiscible liquid, as the beginning of a systematic investigation of the influence by these factors on the breakup of jet. The dependence of the initial amplitude of surface disturbances on the nozzle geometry is presented for evaluating the effect of the nozzle length on the breakup length of laminar liquid jet in the air and in the immiscible liquid.

§ 1. Introduction

It is important in many industrial operations to inject one liquid from a nozzle into the air and into another immiscible liquid. At low injection velocities uniform size drops are formed directly at the nozzle. At higher injection velocities a liquid jet issues from the nozzle and breaks into drops. Although the behavior of the liquid jet has been investigated experimentally and theoretically, many problems have remained unsolved. For example, the effect of the turbulence in the nozzle or the extent of development of the velocity profile upon the behavior of liquid jets has been little studied.

Miesse⁴⁾ reported that the turbulent breakup length of liquid jets injected into the air would be a function of the shape of orifice. Grant and Middleman²⁾ found that the critical velocity of liquid jets injected into the air was affected by the nozzle length. Furthermore, the first author⁷⁾ found the effect of nozzle length on the breakup of liquid jet in the immiscible liquid. However, there is as yet no literature that deals with fundamental studies, and many problems are to be solved. Especially, the effect of the nozzle length on the breakup of jet must be systematically investigated.

In this work the breakup length of the laminar jet injected from various nozzles into the air and the immiscible liquid was measured to

investigate experimentally the effect of the nozzle length on the stability of liquid jet.

§ 2. Experimental Apparatus and Procedure

2-1 Liquid Jet in Air

A schematic flow diagram of experiment is shown in Fig. 1. A gear pump ② circulated

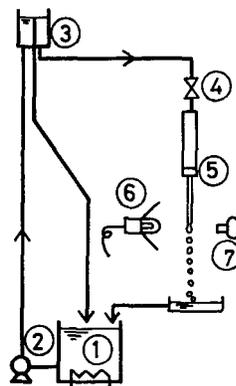


Fig. 1. Experimental apparatus for jet in liquid-air systems.

1. liquid reservoir
2. gear pump
3. constant head device
4. valve
5. nozzle
6. xenon tube
7. camera

the liquid from a liquid reservoir ① through a constant head device ③, a valve ④ and a nozzle ⑤, and back to the reservoir. A jet issued downward into the air from a nozzle.

Most of nozzles used in this experiment were

constructed from drilled brass disks and lods mounted to the vinylchloride pipe as shown in Fig. 2-a. Longer nozzles were constructed from copper tubes and from hypodermic tubes of stainless steel as shown in Fig. 2-b. These

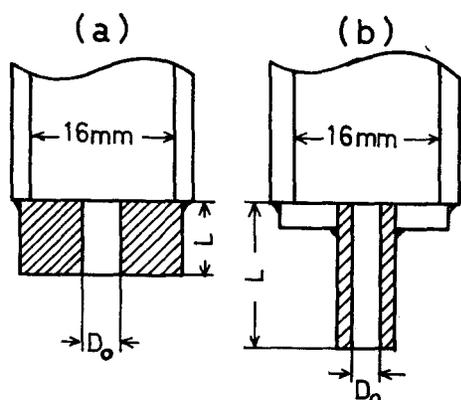


Fig. 2. Geometry of nozzles

Table I Nozzle Dimensions

Nozzle	Diameter cm	L/D_0	Nozzle	Diameter cm	L/D_0
1-1*	0.050	12.0	5-9	0.200	15.1
2-1*	0.090	22.2	5-10*	0.215	17.2
3-1	0.105	0.69	6-1	0.259	0.61
3-2	0.112	1.74	6-2	0.252	0.76
3-3	0.114	2.68	6-3	0.253	1.96
3-4	0.108	6.42	6-4	0.253	3.91
3-5	0.108	9.29	6-5	0.256	7.02
3-6	0.100	15.3	6-6	0.260	7.64
3-7	0.100	20.3	6-7	0.254	12.4
4-1	0.162	0.44	6-8*	0.254	20.3
4-2	0.157	1.26	6-9*	0.254	25.1
4-3	0.162	1.82	7-1	0.300	0.52
4-4	0.156	3.10	7-2	0.303	0.83
4-5	0.157	6.96	7-3	0.307	1.47
4-6	0.157	9.52	7-4	0.314	2.08
4-7	0.160	13.7	7-5	0.305	7.56
4-8	0.164	18.3	7-6	0.318	10.4
4-9*	0.157	22.6	7-7	0.310	15.8
5-1	0.203	0.35	8-1	0.405	0.79
5-2	0.204	0.95	8-2	0.405	1.48
5-3	0.208	1.45	8-3	0.408	1.95
5-4	0.217	1.80	8-4	0.402	3.92
5-5	0.217	3.69	8-5	0.403	6.96
5-6	0.210	7.15	8-6	0.410	9.74
5-7	0.210	9.93	8-7	0.413	14.5
5-8*	0.215	14.4			

Asterisk (*) indicates tubes

nozzles were examined under a microscope. The dimensions of them are given in Table I. The nozzles were coated with the paraffine to prevent from being wetted with the liquid.

The glycerine aqueous solution and the water were used in this experiment. The physical properties of them are given in Table II.

Table II Physical properties of experimental systems

System No.	Substance	Density g/cm ³	Viscosity c. p.	Surface tension dyn/cm	Working temperature °C
1	Glycerine aq. (approx. 45wt%)	1.110	3.68	67.9	30
2	Water	0.998	1.00	72.7	20

The average injection velocity of the dispersed liquid was measured by timed volume of effluent liquid. The breakup length was observed by a stroboscope with a xenon tube and measured from negative films exposed by high speed flash.

2-2 Liquid Jet in Immiscible Liquid

Figs. 3-a and 3-b show schematic flow diagrams of experiment for denser liquid jets and lighter liquid jets in the immiscible liquid, respectively. The dispersed liquid pumped up to a constant head device (3) flowed through a temperature regulator (4) and through a needle valve (5), and issued into the continuous liquid from a nozzle (6). The liquid dispersed into the continuous liquid was discharged from a test section (7) through an overflow tube (10). The test section was a rectangular column (5 × 10 × 50 cm), whose front was made of glass. The experimental apparatuses were set in an air bath (14) for the purpose of maintaining both phases at a constant temperature.

The nozzles shown in Table I were used in this experiment. Table III shows physical properties for experimental systems, and all liquid pairs were mutually saturated prior to the experiment. The average injection velocity of dispersed liquid was measured by timed volume of discharged liquid from the overflow tube. The breakup length of jets was measured from negative films exposed by the high speed flash.

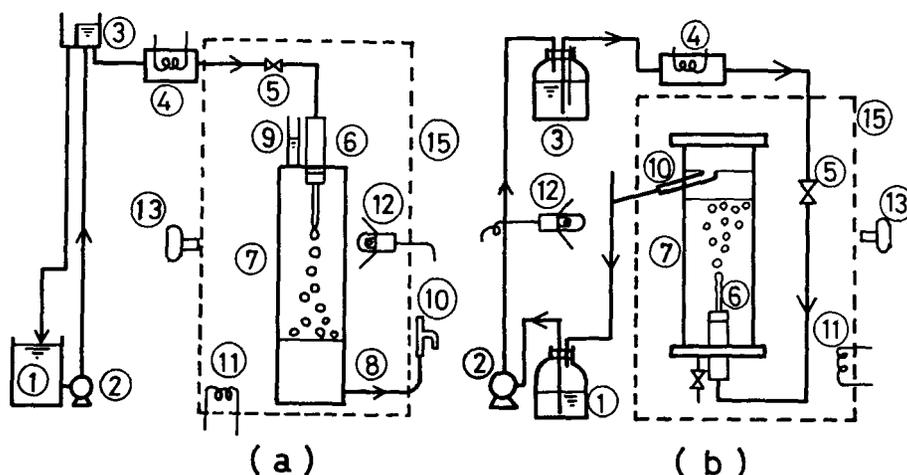


Fig. 3. Experimental apparatus for jet in liquid-liquid systems.

(a) Dispersion of denser liquid. (b) Dispersion of lighter liquid.

1. liquid reservoir 2. pump 8. constant head device 4. temperature regulator
 5. needle valve 6. nozzle 7. test section 8. outlet pipe 9. air-out pipe
 10. overflow tube 11. heater 12. xenon tube 13. camera 14. air bath

Table III Physical properties of experimental systems

System No.	Dispersed phase			Continuous phase			Interfacial tension dyn/cm	Working temperature °C
	Substance	Density g/cm ³	Viscosity c. p.	Substance	Density g/cm ³	Viscosity c. p.		
3	Water	0.996	0.864	Kerosene	0.778	1.240	42.6	26.5
4	Kerosene	0.780	1.037	Glycerine aq.	1.027	1.059	41.0	30

§ 3. Experimental Results and Discussions

3-1 Breakup Pattern

The breakup pattern of the liquid jet issued from the nozzle was observed as same as that of previous works^{1,2)}. The liquid simply drips out of the nozzle at very low injection velocities and forms a laminar jet beyond the jetting velocity, and at higher injection velocities a turbulent jet issues from the nozzle.

Fig. 4 shows a series of photographs of the water jet injected into the air from the nozzle 5—8, the breakup length of which is plotted in Fig. 8. When the injection velocity increases over the jetting velocity, the liquid forms a laminar jet whose breakup length increases with the velocities and becomes the maximum at the critical velocity. At the region past the critical velocity the breakup length decrease steeply with the injection velocities. In this region the liquid forms a transient jet. Photo.

a shows dripping at the nozzle. A typical laminar jet is presented in photo. b. The laminar jet is seen to break only by symmetrical disturbances. Photo. c shows the jet nearly at the critical velocity, the breakup of which seems to be as same as that shown in b. In the next instant, however, the jet breaks at the upper point shown by an arrow because of the initiation of surface disturbances which have larger amplitude, so, the breakup point fluctuates in wider range than at the lower velocities. Photos. d and e show the breakup at the region immediately past the critical velocity. In this region, the jet becomes unstable and has a tendency to break into segments. The reason of such a phenomena may be considered that the initial amplitude of disturbance fluctuates in very wide range. Photos. f and g show the turbulent jet, and the breakup length increases with the injection velocity again. The turbulent jet seems to break by sinuous disturbances or waves.

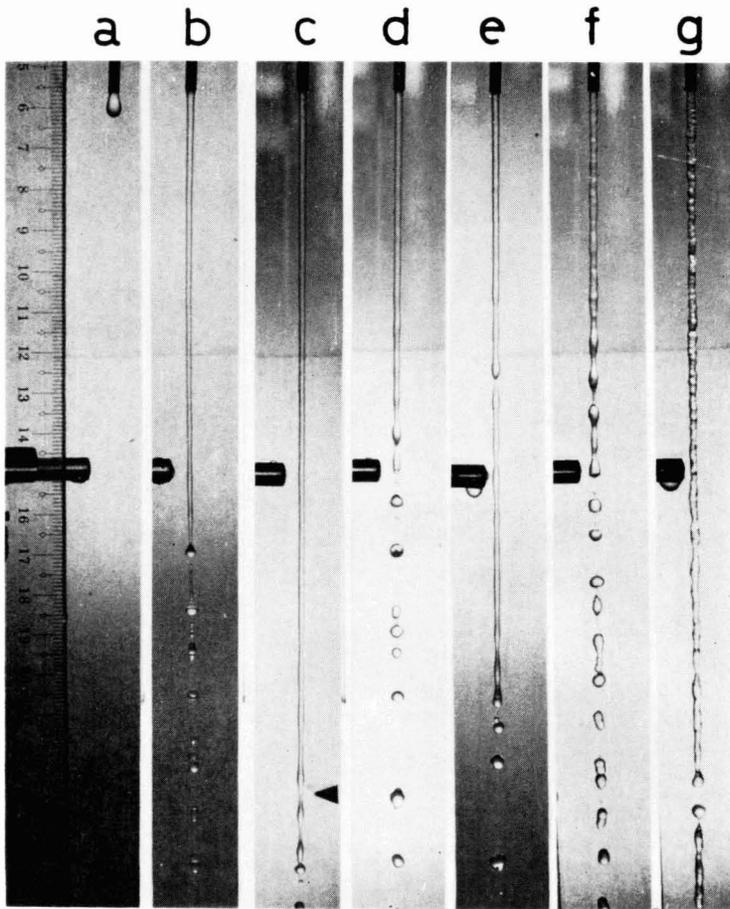


Fig. 4. Photographs of water jet from nozzle 5-8.

- (a) $u_0 = 4.59 \text{ cm/sec}$
 (b) $u_0 = 57.4 \text{ cm/sec}$
 (c) $u_0 = 91.9 \text{ cm/sec}$
 (d) $u_0 = 106.9 \text{ cm/sec}$
 (e) $u_0 = 109.4 \text{ cm/sec}$
 (f) $u_0 = 220.1 \text{ cm/sec}$
 (g) $u_0 = 441.8 \text{ cm/sec}$

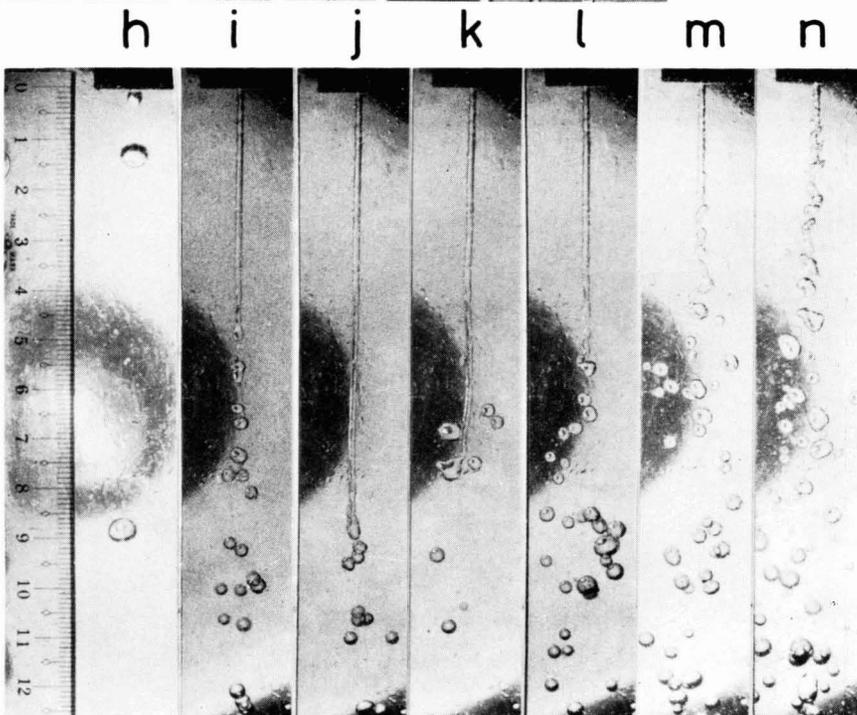


Fig. 5. Photographs of water jet in kerosene from nozzle 4-7.

- (h) $u_0 = 10.4 \text{ cm/sec}$ (i) $u_0 = 33.1 \text{ cm/sec}$ (j) $u_0 = 47.9 \text{ cm/sec}$ (k) $u_0 = 47.9 \text{ cm/sec}$
 (l) $u_0 = 56.3 \text{ cm/sec}$ (m) $u_0 = 77.6 \text{ cm/sec}$ (n) $u_0 = 143.8 \text{ cm/sec}$

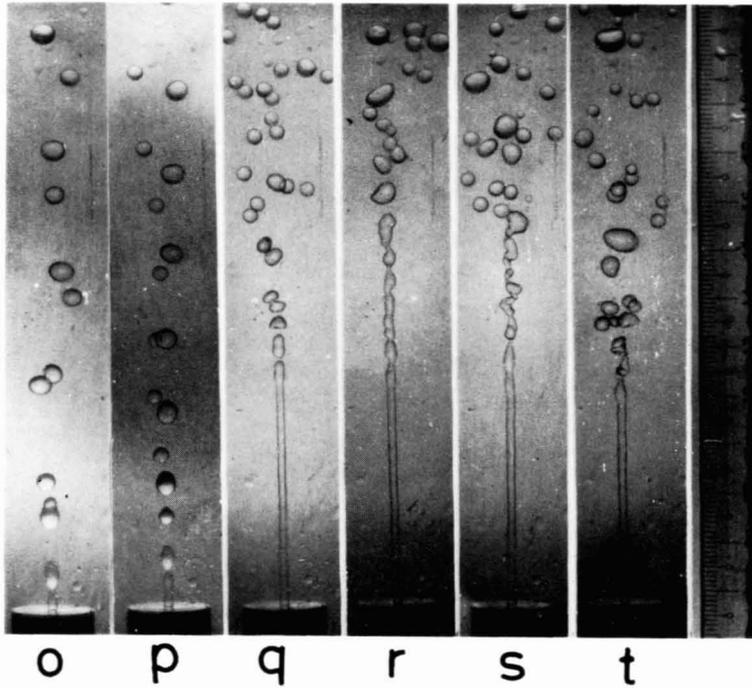


Fig. 6. photographs of kerosene jet in glycerine aqueous solution from nozzle 5—9.
 (o) $u_0=22.2\text{cm/sec}$ (p) $u_0=25.9\text{cm/sec}$ (q) $u_0=40.5\text{cm/sec}$
 (r) $u_0=53.0\text{cm/sec}$ (s) $u_0=65.5\text{cm/sec}$ (t) $u_0=74.5\text{cm/sec}$

Fig. 5 shows a series of photographs of the water jet injected into the kerosene from the nozzle 4—7, and also photographs of the kerosene jet in the glycerine aqueous solution are presented in Fig. 6. Photos. h and o show dripping, Photos. i and q show the laminar jet which is disrupted by symmetric disturbances as same as liquid jets in the air. Laminar jets seem to break into uniform size drops. Photos. j, k and r show the breakup nearly at the critical velocity. The jets in this region are very unstable, as is evident from the fact that **j** and **k** are exposed at the same velocity. Turbulent jets are shown in Photos. l, m, s and t. At very high velocities the dispersed liquid forms sprays as shown in Photo. n. It is evident from the above observation that the flow pattern of the denser liquid injected into the immiscible liquid are the same as that for the lighter liquid injected into the immiscible liquid; and that the liquid drips out of the nozzle and forms laminar jets, turbulent jets and sprays as the injection velocity increases.

The flow pattern and the breakup pattern of liquid jets in the air are analogous to those of liquid jets in the immiscible liquid except at very high velocities as described above.

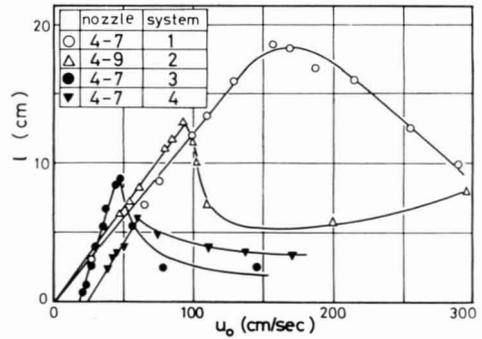


Fig. 7. Breakup curves for jets in some systems.

Fig. 7 shows breakup curves for four systems, which are obtained by plotting breakup lengths against injection velocities. The breakup length of laminar jets in both of the air and the immiscible liquid increases being proportional to injection velocities, and decreases with injection velocities when it exceeds the critical velocity. At higher injection velocities, liquid jets in the air issue as turbulent jets whose breakup length increases with velocities, while the liquid injected into the immiscible liquid forms a spray, and the breakup length decreases with velocities. On the other hand, extrapolating lines of laminar breakup data

for liquid jets in the air pass through an origin, but those for jets in the immiscible liquid do not through an origin. It may be supposed as the reason of this phenomena that the surface velocity of liquid-liquid jets is lower than the average injection velocity.

3-2 Effect of Nozzle Length

From the observation of the breakup length of the liquid jets injected into the air and into the immiscible liquid from the nozzles presented in Table I, it is evident that the behavior of the liquid jets in both systems are influenced not only by the nozzle diameter but by the nozzle length.

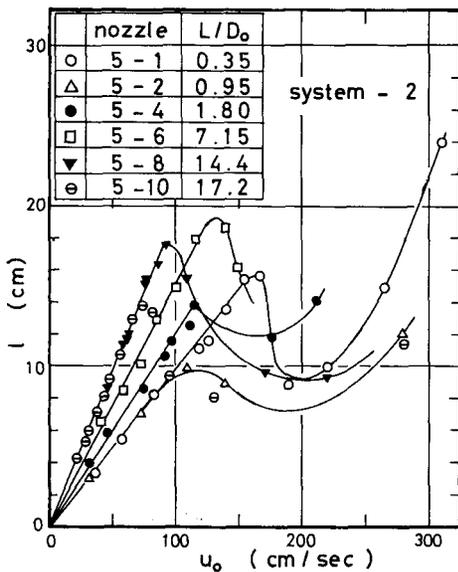


Fig. 8. Effect of nozzle length on breakup length of water jet.

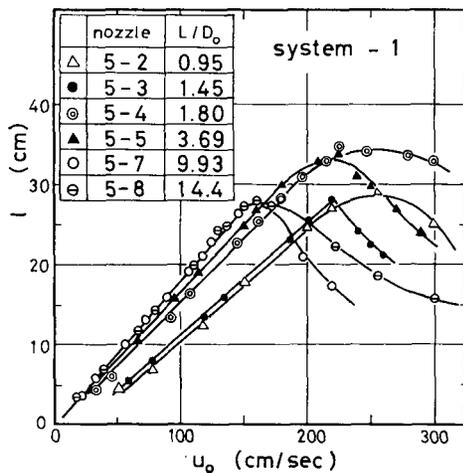


Fig. 9. Effect of nozzle length on breakup length of glycerine aqueous solution jet.

Fig. 8 shows one of experimental results about the effect of the nozzle length for water jets in the air, and Fig. 9 shows that for glycerine aqueous jets in the air. Figs. 10 and 11 show

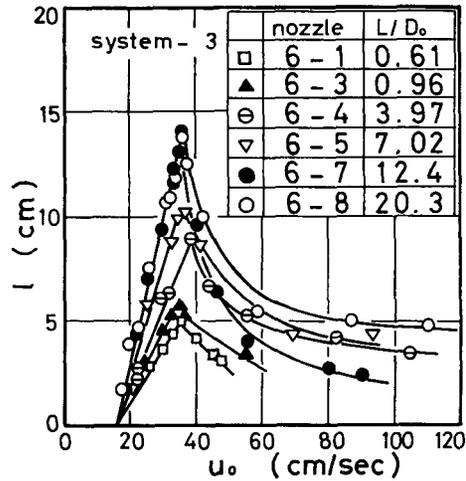


Fig. 10. Effect of nozzle length on breakup length of water jet in kerosene.

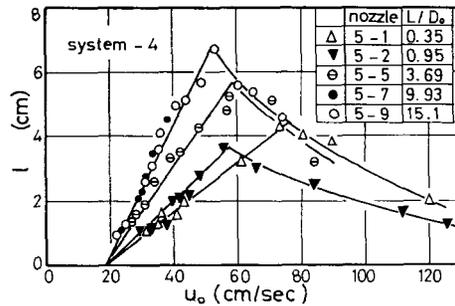


Fig. 11. Effect of nozzle length on breakup length of kerosene jet in glycerine aqueous solution.

the experimental results for liquid jets in the immiscible liquid. The behavior of liquid jets in all systems is apparently influenced by the nozzle length. The same effect is observed for other nozzles of different diameter. The results from the above observation are as follows ; the laminar breakup length of the liquid jet in both of the air and the immiscible liquid increases with the nozzle length, and approaches to a constant value for each diameter when the ratio of nozzle length to the nozzle diameter exceeds a critical ratio. The critical ratio is about 15 for the water jet in the air, about 10 for the glycerine aqueous solution jet in the air and about 10 for both jets of the denser and lighter liquid in the immiscible liquid, within the limits of this experiment. (cf. Figs. 12 and 13.)

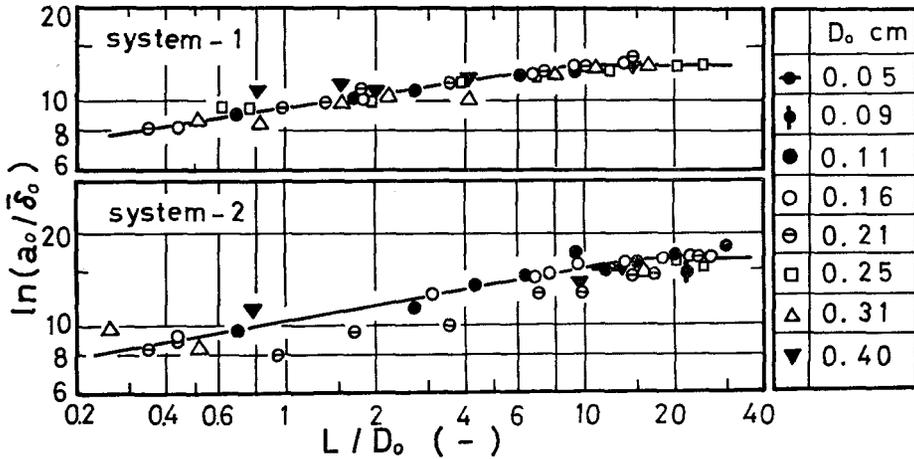


Fig. 12. Variation of initial amplitude of disturbances for liquid-air systems with nozzle length.

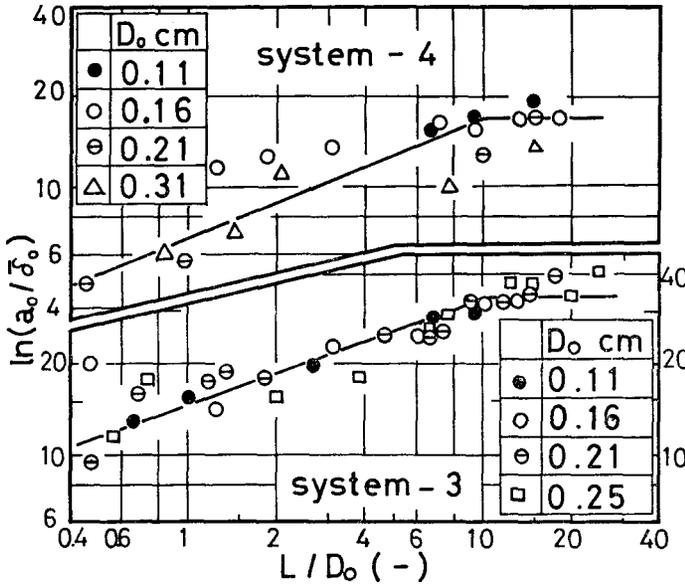


Fig. 13. Variation of initial amplitude of disturbances for immiscible liquid-liquid systems with nozzle length.

The critical velocities from the laminar to the transient jet in the air have a tendency to decrease with the nozzle length as shown in Figs. 8 and 9, but on the contrary, those from the laminar to the turbulent jet in the immiscible liquid are independent of it. While the dependence of the critical velocity upon the nozzle length has found in the previous work²⁾, the quantitative correlation between them has not yet been clear.

Although the behavior of the liquid jets in both of the air and the immiscible liquid are influenced by the nozzle length, the breakup pattern for the longer nozzle are hardly distinguished from that for the thinner orifice.

3-3 Initial Amplitude of Surface Disturbances

It is known that the breakup of liquid jet can be reasonably explained by the following model^{3,8)}. Small disturbances are initiated on the jet surface as a result of pressure fluctuations or turbulences in the nozzle, when the liquid jet issues from the nozzle exit. All disturbances with a wavelength greater than the jet circumference increase exponentially with the time and destroy the jet into drops.

Fig. 12 shows the value of $\ln(a_0/\bar{\delta}_0)$ for the liquid jet in the air, and Fig. 13 shows that for the liquid jet in the immiscible liquid. In these figures, $\ln(a_0/\bar{\delta}_0)$ are plotted against the ratio of nozzle length to the nozzle diameter.

The values of $\ln(a_0/\bar{\delta}_0)$ in these figures are calculated from following equations.

For the noncylindrical liquid jet in the air⁶⁾.

$$\alpha \cdot \gamma \cdot \left\{ \ln \left(\frac{a_0}{\bar{\delta}_0} \right) + \ln X^{-2} \right\} + \sum_{n=1}^{\infty} (-1)^{n+1} \cdot \frac{\gamma^n}{6+n} (X^{6+n} - 1) = 0,$$

where

$$\alpha = \frac{1}{4} \cdot \sqrt{(g^2 \cdot D_0^3 \cdot \rho_D) / (u_0^2 \cdot \sigma)},$$

$$\gamma = 3 \cdot \mu_D / \sqrt{\rho_D \cdot D_0 \cdot \sigma}$$

and

$$X = \{(2 \cdot g \cdot l / u_0^2) + 1\}^{-\frac{1}{8}}.$$

For the liquid jet in the immiscible liquid⁵⁾.

$$\frac{l}{D_0} = \left(\ln \frac{a_0}{\bar{\delta}_0} \right) \left\{ \sqrt{\frac{\rho_D \cdot D_0}{\sigma}} + 14.1 \left(\frac{\mu_D}{\mu_C} \right)^{-0.45} \cdot \frac{\mu_D}{\sigma} \right\} (u_0 - u_j).$$

The value of $\ln(a_0/\bar{\delta}_0)$ increases with the nozzle length and reaches to a constant value beyond the critical ratio of the nozzle length to the diameter, as shown in Figs. 12 and 13. In other words, the initial amplitude of disturbances $\bar{\delta}_0$ decreases with the nozzle length approaching some saturation values.

The experimental results described above can be well explained by the following consideration. The effect of the nozzle length on the laminar breakup length may be due to the dependence of the initial amplitude of surface disturbances upon it. The turbulences or the pressure fluctuations generated at the nozzle entrance dissipate into smaller and smaller one passing through the nozzle. As disturbances on the jet surface are initiated as a results of the turbulence at the nozzle exit, the initial amplitude of disturbances at the exit of the longer nozzles becomes smaller than that for the thinner orifice. In other words, $\ln(a_0/\bar{\delta}_0)$ increases with nozzle length to approach some saturation values. Therefore, the laminar breakup length is consequently affected by the nozzle length.

§ 4. Conclusions

The behavior of liquid jet in the air and in the immiscible liquid was investigated experimentally, and following results were obtained.

1) The breakup pattern of liquid jets in both systems are analogous to one another. As the injection velocities of dispersed liquid become greater, the flow pattern of liquid jet shows

the dripping, the laminar jet and the turbulent jet.

2) The laminar breakup length increases with the nozzle length and approaches to some saturation values beyond the critical ratio of the nozzle length to the nozzle diameter. The critical ratio is about 15 for the water jet in the air, about 10 for the glycerine aqueous solution jet in the air and about 10 for both jets of the denser and lighter liquid in the immiscible liquid. It is considered that the initial amplitude of the surface disturbance is affected by the nozzle length.

Nomenclature

- a_0 : radius of nozzle [cm]
- D_0 : diameter of nozzle [cm]
- g : gravitational acceleration [cm/sec²]
- l : breakup length of jet [cm]
- L : nozzle length [cm]
- u_0 : average injection velocity [cm/sec]
- u_j : jetting velocity [cm/sec]
- $\bar{\delta}_0$: initial amplitude of disturbance [cm]
- ρ : density of liquid [g/cm³]
- σ : interfacial tension [dyn/cm]
- μ : viscosity of liquid [g/cm·sec]

Subscripts

- C : continuous phase
- D : dispersed phase

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