

Study on the breakup lengths of free round liquid jets

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Abstract: An experiment was conducted to measure the breakup lengths of water jets with a high speed video camera for Weber numbers from 0 to about 1.1×10^3 . The initial jet diameters are changed from 0.3 mm to 1.0 mm. The results indicate that at low jet velocity the breakup lengths of the jets are increased linearly from 0 to a maximum value. At the Weber number about 20 the breakup length of the jet reaches its maximum value for different initial jet diameter. A computation based on the dispersion equation is conducted to study the relationship between the growth rate of the jet surface wave and the maximum breakup length. The computations show that the maximum growth rate for the axisymmetric surface wave has a turning point at Weber number about 20, and that agrees well with the experiments.

Key words: breakup length; high speed camera; surface wave; growth rate; dispersion equation

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Introduction

Breakup and atomization of round liquid jets had been widely used in internal combustion engines, gas turbines, and liquid rocket engines. Recently, with the development of scramjet engines and the deepening of fuel atomization research, it attracts much interest and has been studied all over the world again^[1,2]. Experiments were conducted to study the breakup mechanisms usually by optical instruments which were used to take photographs of the breakup process. Theoretical studies were conducted to compute the surface wave growth rate using stability theories of the surface wave to describe the breakup phenomena.

Morozumi et al^[3] carried out an experimental study to investigate the growth and the structures of surface disturbances in a round turbulent water jet with a coaxial airflow. And he

concluded that when the momentum of the airflow at the nozzle exit was superior to that of the water jet, the effect of the asymmetric disturbances on the jet breakup was comparable to that of the axisymmetric disturbances. Arai et al^[4] conducted an experiment on the surface wave transition before breakup on a laminar liquid jet and found that when the surface wave grew up to the large amplitude wave near the breakup point, it changed rapidly from regular to irregular wave. Sallam et al^[5] made experiments on the breakup of a turbulent jet in a gaseous atmosphere and he found three liquid column breakup modes: a weakly turbulent Rayleigh-like breakup mode for $We < 300$ and $Re < 5\,000$, a turbulent breakup mode for $600 < We < 30\,000$, and an aerodynamic bag/shear breakup mode for $We > 30\,000$. For the first two modes in his theory, relationships of breakup length with Weber number were concluded, respectively. And for

the aerodynamic bag/shear breakup mode relationship of breakup length with liquid-air density ratio was concluded. Zhu et al.^[6] measured the breakup length for different breakup regimes and concluded empirical relationships of the breakup length with Reynolds number. Lin^[7] predicted the variation of breakup length with jet velocity and his theory presented two evolutions of the jet breakup length followed the peak when further increasing the jet velocity to a high value.

In order to find out the variation of breakup length initial jet diameter and to verify Lin's prediction, an experiment measuring breakup length of the water jet with a high-speed video camera is conducted in this paper. And the initial jet diameters range from 0.3 mm to 1 mm. A dispersion equation that accounts for the growth rates of round liquid jets surface waves is derived in this paper to interpret the Weber number when breakup length came to maximum in experiment.

1 Experimental setup

Figure 1 shows the schematic of the experimental setup which includes water tank, pipes, pressure gauge, nozzle and high-speed video. The water is driven by high pressure air up to 0.8 MPa. The nozzle diameters are 0.3 mm, 0.5 mm and 1.0 mm, respectively, and the length-diameter ratios of all the nozzles are kept to be 40. The exposure time of the high-speed video with the type X-Stream VISION Digital Camera is set to be 15 microseconds and the framing rate is more than 10 000.

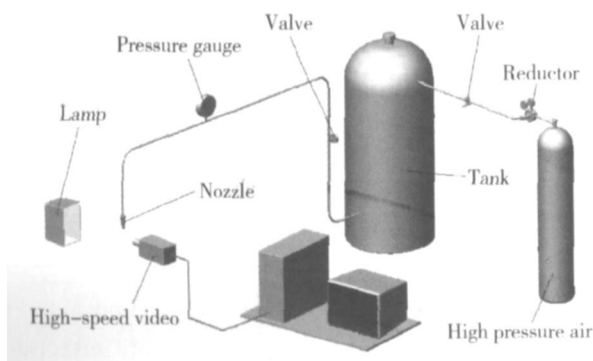


Fig. 1 Schematic of the experimental setup

2 Experimental results and discussions

2.1 Breakup regimes

The parameters used in this paper are defined as follow.

$$Re_L = \rho_L U_L d / \mu_L$$

$$We_L = \rho_L U_L^2 d / \sigma$$

$$Oh = We_L^{1/2} Re_L^{-1} = \mu_L / (\rho_L \sigma d)^{1/2}$$

Where Re_L is the jet Reynolds number, We_L is the Weber number, Oh is the Ohnesorge number of the jet, U_L is the liquid velocity at the nozzle exit, ρ_L is the liquid jet density and d is the initial jet diameter.

Figure 2~ 4 show the breakup process of the jets with diameter 0.5 mm at Reynolds number from 630 to 7253 at a fixed Ohnesorge number 0.00527. The framing rate of the high-speed video camera is 10710, and the exposure time is 15 microseconds.

Figure 2 shows the typical photograph of the round jet at low Reynolds number 630. The flow is from right to left side in the picture. The distance from the right end of the photograph to the exit of the jet nozzle is 52 times of the initial jet diameter. In this photograph, it can be seen that the jet surface is smooth and there are no surface waves on the jet near the right end. But in the downstream location of the jet, the liquid jet is affected by the axisymmetric surface wave of the jet surface. The shape of the cross section of the jet is cylindrical. With the growth of the axisymmetric surface wave length, the jet is finally broken up and the large droplets with nearly the same size are formed. Figure 2 shows the typical Rayleigh jet breakup regime.



Fig. 2 Photograph of Rayleigh regime

Figure 3 shows the typical photograph of the round jet at further increasing Reynolds number 1840. The distance from the right end of the photograph to the exit of the jet nozzle is 4 times of the initial jet diameter. It can be seen

that the jet surface is deformed like a “snake”. Because of the further increasing jet velocity, the oscillations of the surface waves are augmented. The surface waves of the jet are asymmetric, so the sinuous jet could be observed in this photo. The shape of the cross section of the jet could still be approximated to be cylindrical. Liquid breakup occurs further downstream and the droplet size is almost the same as that of Rayleigh breakup. It is the typical First Wind-Induced regime.



Fig. 3 Photograph of First Wind-Induced regime

Figure 4 shows the typical photograph of the water jet at the Reynolds number 7253. The distance from the right end of the photograph to the exit of the jet nozzle is 30 times of the initial jet diameter. It should be pointed out that the shape of the jet deforms from the beginning at the exit of the nozzle. And it can be seen that the surface wave length is shorter than that in Figure 3. Meanwhile, the surface waves become the high order asymmetric waves, which implied that the shape of the cross section of the jet is no longer cylindrical. Figure 4 represents the typical Second Wind-Induced regime.



Fig. 4 Photograph of Second Wind-Induced regime

The breakup process of the jet with Reynolds number ranging from 129 to 1165 displays the feature of Rayleigh regime as shown in Figure 2. When the Reynolds numbers vary from 1165 to 3907, the breakup regime of the jet falls into First Wind-Induced regime. If the Reynolds numbers are larger than 3900, the breakup regime of the jet is Second Wind-Induced regime. The variation of the breakup regime with Reynolds number at the fixed Ohnesorge number agrees well with the results of Liu^[1] and is shown in Figure 5. Line AB, BC and CD represents the Rayleigh regime, First Wind-Induced regime and Second Wind-Induced regime, respectively.

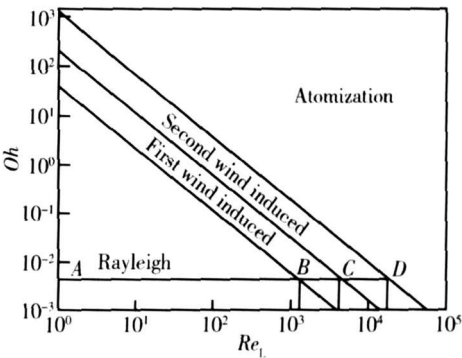


Fig. 5 Breakup regimes of round liquid jets in still air

2.2 The effect of jet velocity on the breakup length

The jet breakup length in this paper is defined as the distance from the nozzle exit to the breakup point of the core jet. Figure 6 shows the variation of the breakup length of the jet of diameter 1.0mm with the Reynolds number.

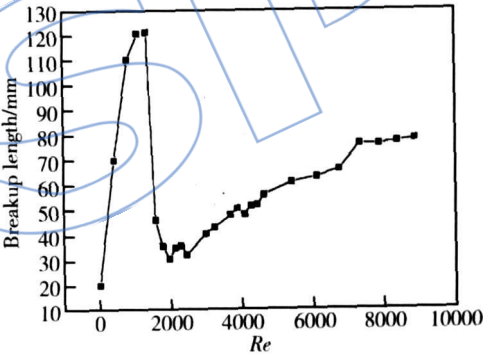


Fig. 6 Variation of jet breakup length with Re for initial jet diameter of 1.0 mm

As shown in Figure 6, the breakup length increases almost linearly when $Re < 1100$ in Rayleigh jet breakup regime. As the jet Re further increases, the gradient decreases before the breakup length reached its maximum value. Subsequent increase of the jet Re results in a rapid decrease of the breakup length. When $Re > 2500$, the breakup length increases gradually. By comparison with the observation of the surface wave, the jet breakup regime for $1100 < Re < 4000$ falls into the First Wind-Induced regime, while the process of the jet breakup for $Re > 4000$ is considered to be the Second Wind-Induced regime. The result agrees well with the schematic diagram of the jet breakup length vs. jet velocity by Lin^[7].

The variation of the maximum breakup length of the jets with Weber numbers is shown in Figure 7. The Weber number for the maximum breakup length for initial jet diameter 1.0 mm is about 20. It is interesting to note that the Weber numbers for the maximum breakup lengths for the other two jet diameters are also found to be about 20. This value is only an approximation and more experiments would be conducted next.

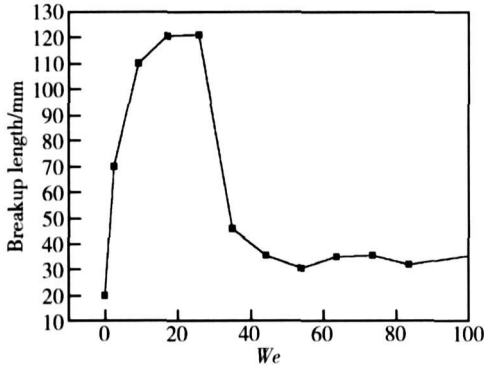


Fig. 7 Variation of jet breakup length with We for initial jet diameter 1.0 mm

2.3 Maximum breakup lengths for different initial jet diameters

Sallam^[5] concluded an empirical relationship between breakup length and We and initial jet diameter for $We < 400$:

$$L_c/d = 5.0We^{1/2} \quad (1)$$

where L_c is the breakup length and d is the initial jet diameter. When other parameters are invariable, equation (1) could be:

$$L_c/C = d^{3/2} \quad (2)$$

where C is a constant and Figure 8 shows the curve of equation (2).

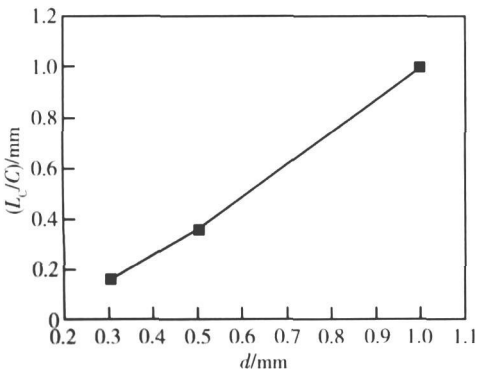


Fig. 8 Variation of L_c/C with initial jet diameter according to Sallam

In this paper, the variation of the maximum breakup length with initial jet diameter is studied experimentally, and Figure 9 shows the results.

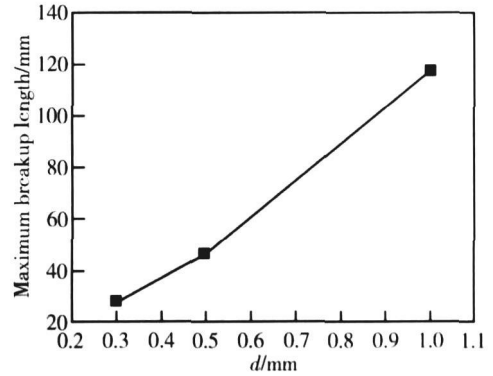


Fig. 9 Variation of maximum breakup length with initial jet diameter

It could be seen that the maximum breakup length increases along with the increasing of the initial jet diameter, and the rate of increasing becomes greater than a linear variation. The experimental result agrees well with Sallam's correlation.

3 Computational analyses

To predict the Weber number corresponding to the maximum breakup length, the computation based on the dispersion relationship is conducted. The fluid is assumed to be incompressible and inviscid. The nonlinear terms are neglected. The resulted dispersion relationship is similar with that of Yang^[8]:

$$(\rho_m + \rho_{2m})\alpha^2 + 2ik\alpha(\rho_{1m}U_1 + \rho_{2m}U_2) - k^2(\rho_{1m}U_1^2 + \rho_{2m}U_2^2) - \frac{k\sigma}{a}[1 - m^2 - (ka)^2] = 0$$

where

$$\rho_m = \gamma_m \rho_1$$

$$\rho_{2m} = \beta_m \rho_2$$

$$\gamma_m = kI_m(ka)/I'_m(ka) =$$

$$I_m(ka) \left\| \frac{dI_m(kr)}{d(kr)} \right\|_{kr=ka}$$

$$\beta_m = -kK_m(ka)/K'_m(ka) =$$

$$K_m(ka) \left\| \frac{dK_m(kr)}{d(kr)} \right\|_{kr=ka}$$

In the previous researches about the surface wave, there are two analysis methods, i. e. temporal and spatial mode^[9-10]. In this paper the

temporal mode analysis method is used. Let $\alpha = \alpha_r + i\alpha_i$.

Then the growth rate can be solved to be $(\alpha_r^*)_m^2 = \gamma_m \beta_m Q (ka)^2 / (\gamma_m + \beta_m Q)^2 + (ka) \cdot [1 - m^2 - (ka)^2] / [We (\gamma_m + \beta_m Q)]$ where $(\alpha_r^*)_m^2$ and We are the square of the dimensionless growth rate for the m th transverse mode and Weber number, respectively, $(\alpha_r^*)_m^2 = (\alpha_r)_m^2 / [(U_1 - U_2)^2 / a^2]$ $We = [d_0 (U_1 - U_2)^2 \rho] / \sigma$ and Q is the density ratio of air to water, $Q = \rho_2 / \rho_1$.

The axisymmetric mode surface wave is realized when $m = 0$. For any integer, $m > 0$, $(\alpha_r^*)_m^2$ represents the growth rate of the m th asymmetric surface wave.

According to the solution of $(\alpha_r^*)_m^2$, the variation of growth rate with wave number at constant m and We can be plotted. For example, Figure 10 shows the variation of growth rate with ka at Weber number 1 000 for $m=1$ mode. The maximum growth rate in Figure 10 was about 10^{-5} , and this maximum value varies with Weber number. Figure 11 shows the growth rate with Weber number for the surface wave with $m=0\sim 3$.

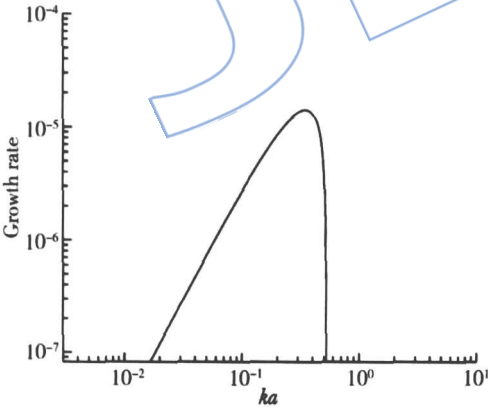


Fig. 10 Variation of growth rate for $m=1$ mode with wave number ka at $We=10^3$

As shown in Figure 11, for $1 < We < 1\,000$ the growth rate of the surface wave is negative if $m > 0$, while positive if $m = 0$. This implied that the axisymmetric surface wave plays a dominant role in the breakup process of the jets under this condition. For $m=0$ mode the curve has a turn-

ing point at Weber number about 20. And for Weber number below 20, the growth rate decreases rapidly. When increasing the Weber number to larger than 20 the surface wave growth rate nearly has no change and the value is close to 0. If the Weber number increases further above 1 000, the growth rate was increased again (shown in Figure 12). So at Weber number about 20 the jet is in a relatively stable state, and the jet breakup length reaches the maximum value. It agrees well with the experiments.

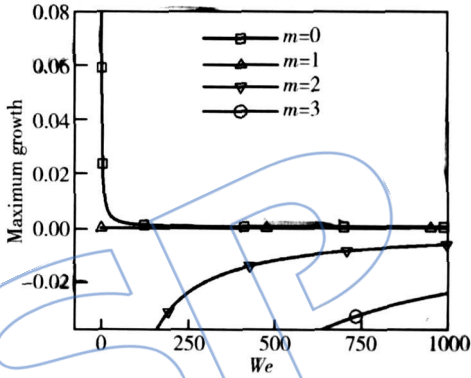


Fig. 11 Variation of growth rate for $m=0$ to 3 mode with We less than 1 000

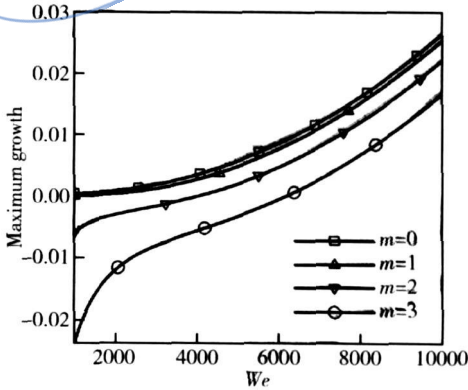


Fig. 12 Variation of growth rate for $m=0$ to 3 mode with We greater than 1 000

4 Conclusions

According to the experiments and computations, some conclusions can be summarized as follow:

When $Re < 1\,100$, the process of the jet breakup is the Rayleigh regime, the surface wave is axisymmetric. The breakup length of the jet is increased linearly from 0 to a maximum value.

The jet breakup for $1\ 100 < Re < 4\ 000$ is classified into the First Wind-Induced regime. The sinuous surface wave is observed, and the breakup length dives down rapidly and then increases gradually.

If the jet velocity is further increased, the jet breakup for $Re > 4\ 000$ is considered to be the Second Wind-Induced regime. The surface waves become the high order asymmetric waves, and the breakup length increases smoothly.

The breakup length of the jet always reaches its maximum value at Weber number about 20 for different initial jet diameter. It agrees well with the computations.

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