

Fluid Dynamics and Transport Phenomena

Experimental research on breakup of 2D power law liquid film[☆]Lixing Xu¹, Zhenyan Xia^{1,*}, Mengzheng Zhang², Qing Du³, Fuqiang Bai³¹ Department of Mechanics, Tianjin University, Tianjin 300072, China² Xi'an Aerospace Propulsion Institute, Xi'an 710100, China³ State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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ABSTRACT

On account of limited knowledge of the breakup of power law liquid film, the process of its disintegration and atomization was studied by using a planar liquid film. A linear stability analysis was adopted to predict the breakup characteristics of the power law film. The predicting formulas of stripping breakup length and diameter of ligament were put forward presently. Through high-speed photography and laser light sheet illumination, different breakup characteristics of flat power law film under different conditions were derived. The characteristic dimension of breakup regimes were defined and extracted. The effects of several parameters (injection pressure, ambient pressure, nozzle structure and fluid property) on the stripping breakup length and spray angle were investigated. The results revealed that increasing both the velocity of liquid film and the ambient pressure facilitated the breakup of film, reduced the stripping breakup length and enlarged the spray angle in different extents. The comparison between theoretical and experimental results was conducted to validate the feasibility of the linear stability theory.

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1. Introduction

The breakup of liquid jet is involved in many industrial processes and practical applications such as farm irrigation, fuel atomization in engines, printing and surface painting. How these applications go on relies strongly on related physical mechanisms. In most of these applications, power law non-Newtonian fluid is referred to, but the corresponding investigation is rather rare. Thus, it is of great significance to investigate the breakup mechanisms in this area.

The linear instability theory can estimate the start of instability of liquid film. What's more, the stripping breakup length, diameter of ligament and drop radius can be figured out by use of linear stability theory.

The basic mechanisms involved in atomization have been studied for many years on planar liquid films and the major achievement has been achieved since Rayleigh [1], Weber [2], Fraser *et al.* [3] and Crapper *et al.* [4] among others. One investigation on the behavior of liquid jets was thanks to Weber who developed the complete solution for a viscous Newtonian liquid jet. Also, Squire [5] proposed a linear stability theory for a liquid sheet of constant thickness evolving in quiescent ambience. Since then analysis of liquid breakup has been focused on the aerodynamic interaction between air and liquid phases which

induces the formation of waves. Those waves are characterized by a wave length, wave amplitude rate and frequency, while the growth of these unstable waves makes the liquid film break up into ligaments and finally into droplets [6].

Several mechanisms were proposed about liquid film especially for Newtonian liquid [7–12]. Especially Nasser Ashgriz [13] provided an overview of the processes that occur in atomization and spray systems and addressed both the classical and theoretical concepts of atomization as well as more recent developments. However, a few studies are available for non-Newtonian liquid jet, particularly power law liquid, which belongs to non-Newtonian liquid with highly nonlinear constitutive equations. Hwang *et al.* [14] investigated the linear stability of power law liquid sheet flowing down an inclined plane. Nevertheless, studies that have been done on the breakup regimes of power law liquid films are rather limited. Gao [15] investigated the temporal instability of power law liquid sheet jets in vacuum with a surface tension gradient, and found that the jet breakup mechanisms depend on the fluid properties and the wave number of thermal disturbances. The instability of viscoelastic liquid jets has been investigated by many authors [16–19]. Brenn *et al.* [18] studied the temporal instability behavior of viscoelastic liquid jets moving in an inviscid gaseous environment theoretically for axisymmetrical disturbances. The corresponding breakup formula was derived, and the linearized stability analysis showed that a jet of viscoelastic fluid exhibits a larger growth rate than a jet of Newtonian fluid with the same Ohnesorge number. Witherspoon and Parthasarathy [20] performed a spatial instability analysis of a viscous liquid sheet

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* Corresponding author.

E-mail address: xia_zhy@hotmail.com (Z. Xia).

that was subjected to equal and unequal gas velocities and discussed the effects of gas velocity on the growth of disturbances for liquid sheets in a range of Reynolds number, Weber number and density ratio. Chang [21] investigated the instability characteristics of power law liquid film jets and proposed the corresponding breakup relation between the growth rate of disturbance waves and the wave number. Yang [22] applied a simple linear stability model to an incompressible viscoelastic liquid cylindrical jet to investigate the breakup characteristics, and also discussed the influence of all parameters in the linear viscoelastic model on the stability of viscoelastic liquid jets. Jin [23] made a study on large eddy simulation of flow field near nozzle of a rectangular jet. Qian [28] presented a comprehensive three-dimensional model of droplet-gas flow to study the evolution of spray in the effervescent atomization spray with an impinging plate.

The ultimate objective of these analyses is to obtain the predictor formula of stripping breakup length and ligament diameter by solving the dispersion equation for non-Newtonian liquid between disturbance growth rate and wave number. However, most previous researches are on Newtonian liquid for putting forward specific predictor formulas. To validate the power law liquid film breakup model, experiments with nozzles of different aspect ratios were conducted in the present study and a high speed camera with laser light illumination was used to present the graphic information of the planar liquid film breakup process. Non-dimensional parameters such as Reynolds number, Weber number and rheology flow index were tested for their effects on the atomization of film flow. In order to verify the accuracy of the theoretical formulas and the reliability of experiment, the comparison of theory and experiment was conducted.

2. Experimental Method and Instrumentation

Fig. 1 shows a schematic diagram of the experimental facilities which consist of three parts: the high temperature and pressure vessel system, the injection system and the optical camera system.

2.1. High temperature and pressure vessel system

High temperature and pressure vessel system presented in Fig. 2 is aimed at offering an experimental environment with proper temperature and pressure, which has the heating equipment fixed inside and is connected externally to the gas inlet connector, safety valve and relief valve. Three inspection windows made of quartz glass are grooved in the axial and radial direction to facilitate the arrangement of light path and photograph shooting. In addition, pressure transmitter is used to adjust the ambient pressure. The internal diameter is 250 mm and the internal depth is 800 mm. The total length of the nozzle is 30 mm and it is inserted into the vessel 10 mm, so that the fully developed flow in the nozzle is ensured.

The pressure inside the vessel (ambient pressure of film flow) is controlled by pumping into high pressure gas of N_2 and SF_6 mixture. The density of SF_6 is as 6 times as that of N_2 , and the physical and chemical properties of SF_6 make it a good choice for managing the ambient gas especially in case of high velocity (Table 1).

2.2. Injection system

The injection of high pressure liquid in the storage tank is controlled by a solenoid valve whose structure matches the characteristics of non-Newtonian fluid well (at the top in Fig. 2), which allowed a high volumetric flow rate. The potential maximum volumetric flow rate meets the experimental requirement superbly. Furthermore, nearly all flow passages between the storage tank and the nozzle are connected smoothly so as to eliminate the great pressure gradient area and reduce the energy loss. Moreover, in order to enhance the cooling effect, the outer surface of the nozzle passage is painted with thermally conductive silicone rubber working together with cooling water jacket. The section of the nozzle orifice is a rectangle with length L_i (2 mm) by width W_i (from 0.3 to 0.7 mm), making the aspect ratio from 2.86 to 6.67.

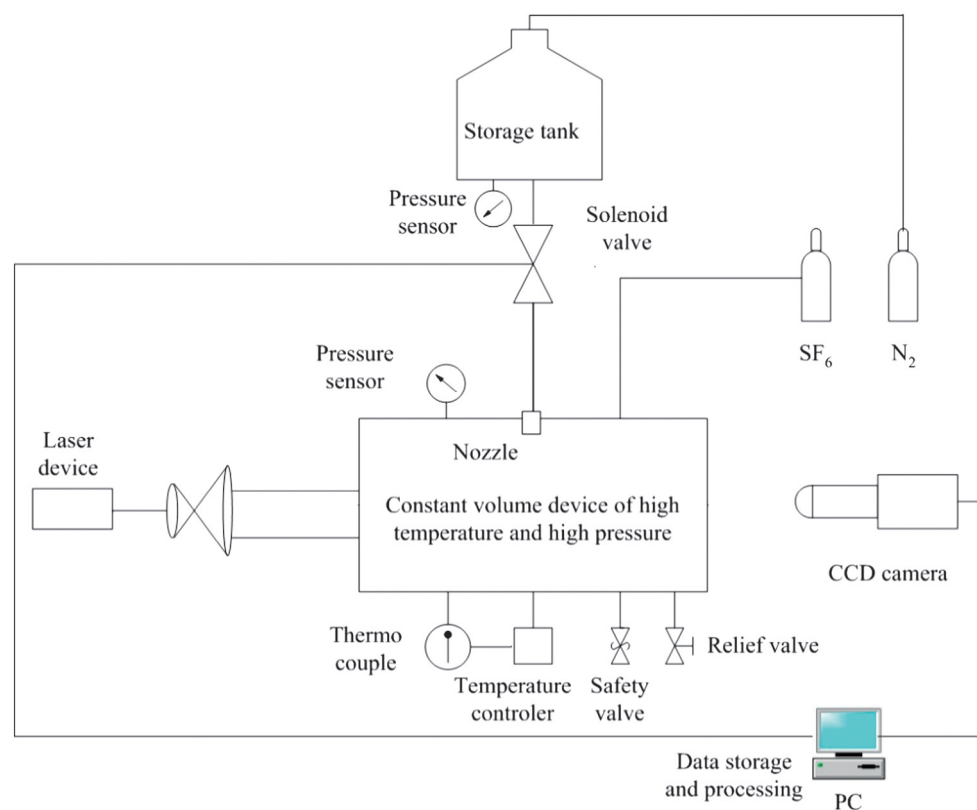


Fig. 1. Schematic diagram of the experimental facilities.

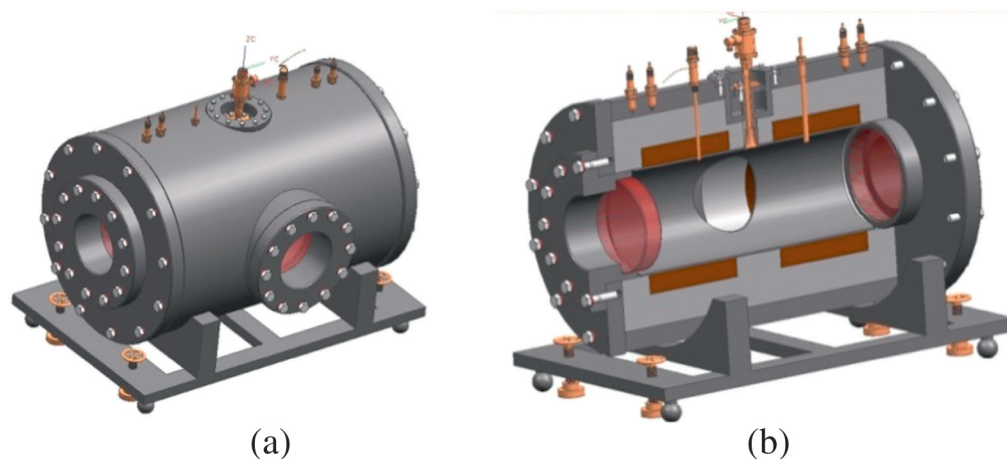


Fig. 2. Schematic diagram of (a) the lateral view of high temperature and high pressure vessel, (b) profile view of high temperature and high pressure vessel.

2.3. Optical camera system

The optical system is built with a high-speed camera and a laser source based on shadowgraph principles to take photos for different conditions such as the aspect ratio of the orifice, the injection pressure, ambient pressure and so on. The camera is FAST.SA 1.1, which captures 1024×1024 pixels/5400 fps or 128×128 pixels/90000 fps, 12 bits. It is equipped with a Nikon Nikkor 50 mm lens. During the filming process, according to the quality of pictures, the system is adjusted to the optimal state by trial and error. A CCD camera starts to transform light signal into electrical signal, and the data is stored on the hard drive connected to the PC. After accomplishment of the capturing images, the software recognizes the data to place all of the necessary files into the same location. By contrast of the shadowgraph by common light with scattering graph by laser light, it is believed that shadowgraph of laser light source is better at capturing the morphology feature of the film flow.

3. Characteristics of Power Law Film Breakup

Typical morphology of power law film breakup is shown in Fig. 3. There exists a uniform, steady potential core zone where the liquid is continuous near the orifice exit. But when the film develops downstream far from the nozzle exit, liquid ligaments come into being from which little droplets are stripped away as described in Fig. 3.

As to the power law non-Newtonian liquid, the breakup characteristic dimensions of film flow could be defined by using that of the Newtonian liquid as reference. However, considering its highly nonlinear constitution equation, the breakup characteristic dimensions are hard to be defined or even extracted especially for film flow. In this work, the stripping breakup length and spray angles are defined as above in Fig. 3, so that the statistics of a great number of optical photographs can be retrieved.

Stripping breakup length L_s is the distance from the orifice to the point where the flow is deformed, torn into ligaments and small droplets stripped away from the edge of the liquid film. The stripping breakup length is a significant parameter to evaluate the disintegration quality.

Table 1
Physical properties

Substance	Density $\rho/\text{kg} \cdot \text{m}^{-3}$	Surface tension $\sigma/\text{N} \cdot \text{m}^{-1}$	Consistency $K/\text{Pa} \cdot \text{s}^n$	Power index n
Water	1000	0.073	1.05	1
Simulant 1	1000	0.073	17.5	0.6
Simulant 2	1000	0.073	7.9	0.5
N ₂	1.25	–	–	1
SF ₆	6.14	–	–	1

Spray angle θ is the field angle that fluid flow develops in the near nozzle exit (less than 10°) in the width direction of film. Spray angle visually reflects the original atomization trend.

When the film starts to break up, the shear appears and fragments of liquid sheet are broken. Then, the surface tension forces these fragments to become unstable ligaments. So the diameter of a cylindrical ligament d_L is used to describe the atomization effect during this process.

3.1. Disturbance mode of power law liquid film

According to the instability theory, for a fluid film injected into a quiescent gas medium, the disturbance will induce unstable surface waves on two gas–liquid interfaces of a liquid sheet. If the phase difference, $\varphi = 0$, it is called sinuous mode; if $\varphi = \pi$, it is named varicose mode as what is shown in Fig. 4.

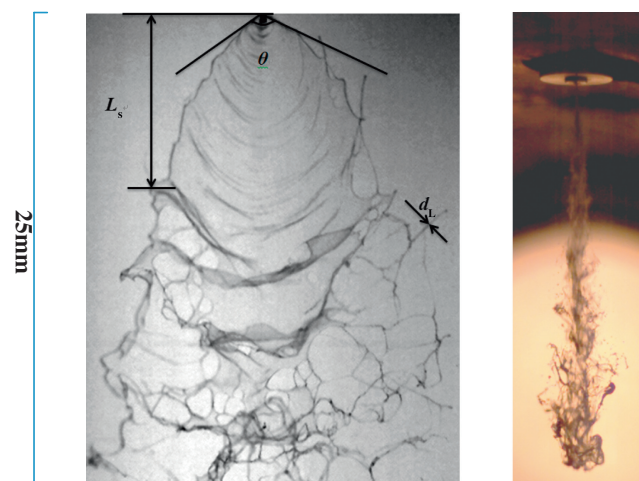


Fig. 3. Experiment determination of stripping breakup length, expansion angle and ligament diameter.

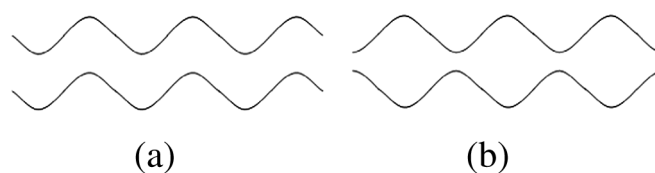


Fig. 4. The disturbance modes: (a) sinuous mode ($\varphi = 0$), (b) varicose mode of liquid film ($\varphi = \pi$).

3.2. Linear instability analysis of power law liquid film

Linearized theory can directly reflect the development of instability on the liquid film with disturbance. In this work, a power law liquid film whose consistency coefficient is K , power index is n and velocity is U_l injected into a static inviscid gas medium is considered. The liquid apparent viscosity μ_l follows a power law equation approximately:

$$\mu_l = K\dot{\gamma}^{n-1} \quad (1)$$

where $\dot{\gamma}$ ($\text{m}\cdot\text{s}^{-1}$) is the shear rate according to Back *et al.* [24],

$$\dot{\gamma} \approx \frac{8U_l}{a} \quad (2)$$

as shown in Fig. 5, where the coordinate system is also denoted.

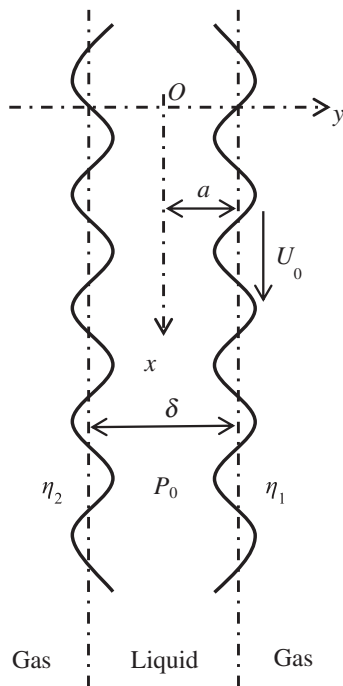


Fig. 5. Schematic of wavy liquid film, surface disturbance and the coordinate system.

3.3. Force balance model on a wavy film

According to Dombrowski *et al.* [3], the equation of motion for liquid film presented in Fig. 5 is derived by considering the forces due to gas pressure, surface tension, liquid inertia and viscosity on an element of a film in the x direction. This element of unit depth is determined as $(2a)dx$ as shown in Fig. 5.

The total gas pressure force on the element is achieved by summarizing the pressure force on the upper and lower surface:

$$F_p = 2k\rho_g U_0^2 y dx \quad (3)$$

where k is the wave number. Force caused by the surface tension on the same element is

$$F_\sigma = 2\sigma \frac{\partial^2 y}{\partial x^2} dx. \quad (4)$$

The inertial force can be calculated as

$$F_i = -\rho_l \left[2a \frac{\partial^2 y}{\partial t^2} + \frac{\partial(2a)}{\partial t} \frac{\partial y}{\partial t} \right] dx. \quad (5)$$

The viscous force acting upon the sheet is

$$F_\mu = \mu_l(2a)k^2 \frac{\partial y}{\partial t} \sin(kx + \varphi) - \frac{\mu_l k \partial(2a)}{U_l \partial t} \frac{\partial h}{\partial t} \cos(kx + \varphi). \quad (6)$$

The total force on the element is

$$F_p + F_\sigma + F_i + F_\mu = 0. \quad (7)$$

For the basic steady flow, the velocity and pressure of both liquid and gas are followed by

$$\mathbf{U}_g = (0, 0) \quad (8)$$

$$\mathbf{U}_l = (U_0, 0) \quad (9)$$

$$P_g = P_0 \quad (10)$$

$$P_l = P_0 \quad (11)$$

where the subscript l and g mean liquid and gas respectively and 0 is for the initial state.

When the film flow interacts with the ambient gas, the interface will be displaced from the equilibrium position $y = a$, thus,

$$\mathbf{U}_j = \bar{\mathbf{U}}_j + \mathbf{u}_j, \quad (j = g, l) \quad (12)$$

$$P_j = \bar{P}_j + p_j \quad (13)$$

$$y(x) = a + \eta(x) \quad (14)$$

where the lower case symbols $\mathbf{u}$ and p are used to signify the unsteady perturbations of the film velocity and pressure and η denotes the fluctuation amplitude.

Considering that the fluid film is subjected to a small distance, which obeys the normal mode as

$$(\mathbf{u}_j, p_j, \eta_1, \eta_2) = (\tilde{\mathbf{u}}_j(y), \tilde{p}_j(y), \eta_a, \eta_{-a}) e^{ikx + i\omega t}, \quad (j = g, l) \quad (15)$$

where η_a, η_{-a} is the initial amplitude, k is the wave number and $\omega = \omega_r + i\omega_i$, in which, real part ω_r denotes disturbance frequency while imaginary part ω_i denotes the growth rate of disturbance wave.

The dispersion relation according to Chang [21] is expressed by

$$\frac{(\omega + i\alpha)^2}{L} \coth(L) + \frac{H\omega^2}{\alpha} + \frac{\alpha^2}{We} = 0 \quad (16)$$

with the following non-dimensional parameters:

$$\alpha = ka, L = la, \omega = \frac{\omega a}{U_0}, G = \frac{ga}{U_0}, We = \frac{\rho_l U_0^2 a}{\sigma}, Re_n = \frac{\rho_l U_0^{2-n} a^n}{K}, H = \frac{\rho_g}{\rho_l}$$

$$L = \alpha \sqrt{\frac{Re_n(\omega + i\alpha)}{Re_n(\omega + i\alpha) + 2n\alpha^2(2G)^{n-1}}}.$$

3.4. Estimation of the stripping breakup length

The dispersion in Eq. (16) can be numerically solved for one variable by keeping other dimensionless parameters specified. Fig. 6(a) gives the dimensionless growth rate ω versus the dimensionless wavenumber α under different conditions. The maximum growth rate, ω_{rmax} , and the dominant wavenumber corresponding with ω_{rmax} , α_{dom} , are related to

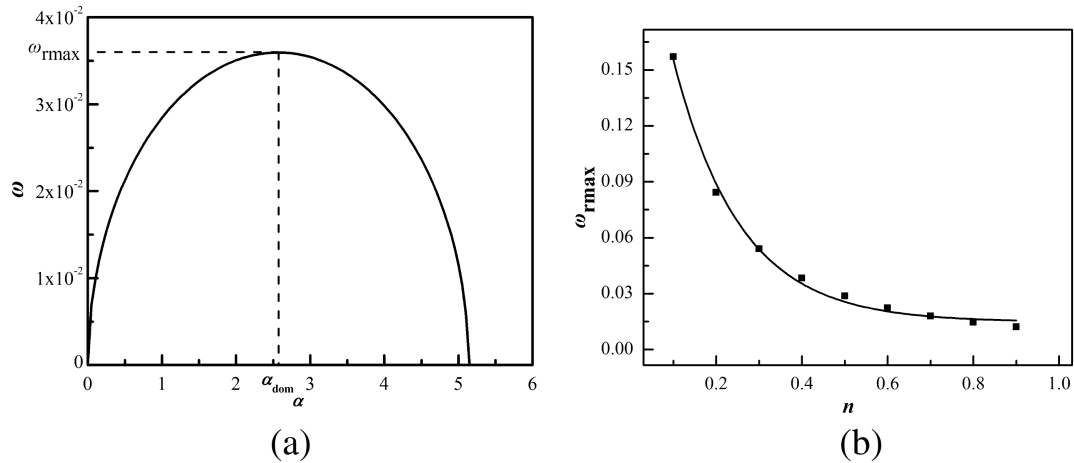


Fig. 6. (a) Schematic diagrams of the instability curves of jets in case of $n = 0.5$ (b) the effect of index n on maximum growth rate ($We = 5240$; $G = 0.000005$; $H = 0.006$; $U_0 = 50 \text{ m} \cdot \text{s}^{-1}$; $\delta = 0.3 \text{ mm}$; $K = 17.5 \text{ Pa} \cdot \text{s}^n$; aspect ratio = 6.67).

the breakup length and scale of jets, respectively. Thus, the relation of the growth rate $\omega_{r\max}$ with power index n varying from 0.1 to 0.9 is obtained like in Fig. 6(b) and it is evident that the maximum growth rate decreases sharply as the power index n increases.

The numerical data in Fig. 6 is fitted into the following form:

$$\omega_{r\max} = A_0(e^{-6.4n} + A_1) \quad (17)$$

where A_0 and A_1 are the correction factors. And the correlation reads:

$$\omega_{r\max} = 0.27(e^{-6.4n} + 0.06). \quad (18)$$

The same way by solving Eq. (16), the relation between maximum growth rate $\omega_{r\max}$ and Reynolds number Re_n increasing from 1 to 2000 is derived. Fig. 7 demonstrates that with the increase of Reynolds number, the maximum growth rate increases linearly. The $\omega_{r\max}-Re_n$ curve indicates that the closer the film flow comes to the turbulence, the easier the film gets broken up.

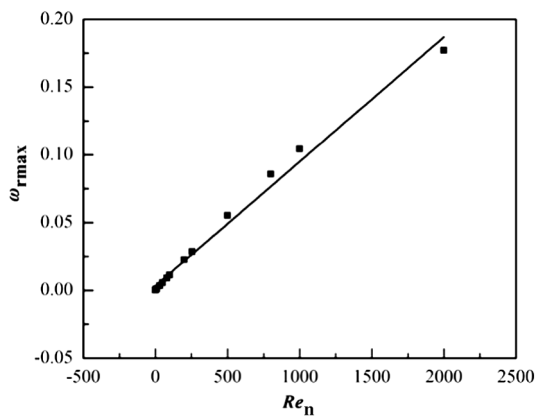


Fig. 7. The effect of Reynolds number on the maximum growth rate ($We = 5240$; $G = 0.000005$; $H = 0.006$; $U_0 = 50 \text{ m} \cdot \text{s}^{-1}$; $\delta = 0.3 \text{ mm}$; $n = 0.6$; aspect ratio = 6.67).

The relation in Fig. 7 may be expressed as

$$\omega_{r\max} = A_2 Re_n + A_3 \quad (19)$$

and the fitted correlation is as follows:

$$\omega_{r\max} = 9 \times 10^{-5} Re_n + 3 \times 10^{-3} \quad (20)$$

Fig. 8 demonstrates the variation of maximum growth rate with Weber number of the liquid film. The maximum growth rate increases substantially with We . In addition, when We increases, the maximum instability moves to the direction of short wave.

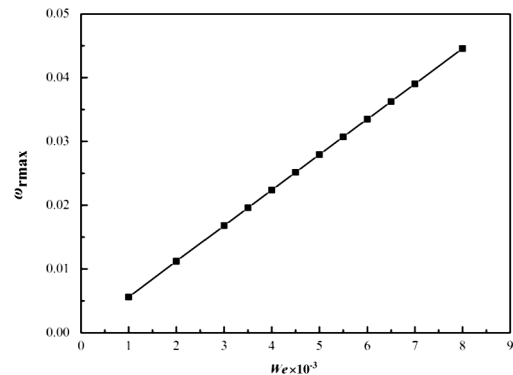


Fig. 8. The effect of Weber number on the maximum growth rate ($Re_n = 260$; $G = 0.000005$; $H = 0.006$; $\delta = 0.3 \text{ mm}$; $n = 0.6$; aspect ratio = 6.67).

The relation of maximum growth rate with Weber number is correlated as follows:

$$\omega_{r\max} = 6 \times 10^{-6} We + 1 \times 10^{-4} \quad (21)$$

Finally, the relation the maximum growth rate versus density ratio H is acquired by linear stability analysis when H increases from 0.001 to 0.15.

Fig. 9 reveals that the maximum disturbance growth rate increases in accord to the density ratio. Hence, increasing density ratio especially increasing the gas density via increasing gas pressure could facilitate the breakup of liquid film.

The relation can be presented in the form of

$$\omega_{r\max} = A_4 H^{1.92} \quad (22)$$

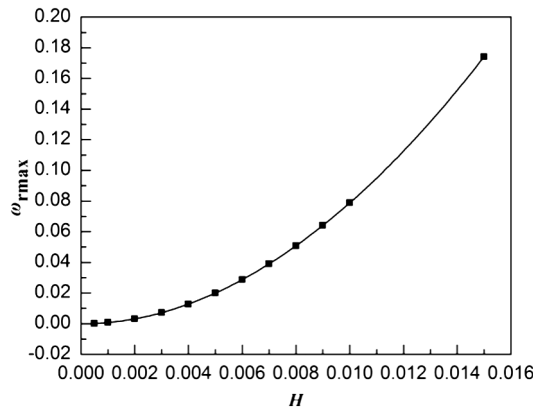


Fig. 9. The effect of density ratio on the maximum disturbance growth rate ($Re_n = 260$; $We = 5240$; $\delta = 0.3$ mm; $n = 0.6$; $K = 17.5$ Pa·sⁿ; aspect ratio = 6.67).

and fitted to the results in Fig. 9 leads to

$$\omega_{r\max} = 573(H - 2.3 \times 10^{-4})^{1.92} + 2 \times 10^{-4}. \quad (23)$$

According to the correlation between the maximum growth rate and the stripping breakup length, the predicting formula of stripping breakup length L_s is proposed as

$$L_s = C \frac{1}{(e^{-6.4n} + A_1) Re_n We H^{1.92}} \quad (24)$$

where C is the correction factor.

As a comparison, York *et al.* [25] argued that when fluctuation amplitude reaches a certain value, the breakup length of the film:

$$L_b = U_l \tau_b = U_l \ln(\eta_b/\eta_0)/\omega_{r\max} \quad (25)$$

the film then starts to break up. The breakup time τ_b can be obtained as

$$\tau_b = \ln(\eta_b/\eta_0)/\omega_{r\max}. \quad (26)$$

$\ln(\eta_b/\eta_0)$ here is defined as the breakup parameter which determines what time the breakup occurs. Weber [2] made the pioneering investigation on this parameter and proposed a value of 12. Kroesser and Middleman [26] obtained a value of 11 for viscous Newtonian liquid. However, some researchers also reported that $\ln(\eta_b/\eta_0)$ should be determined in specific case rather than a general value. The latest investigation by Sarchami *et al.* [27] suggested a correlation for the breakup parameter, which is based on Reynolds and Weber numbers:

$$\ln(\eta_b/\eta_0) = Re_n^{0.07} We^{0.37} \quad (27)$$

where Re_n and We have been defined before.

3.5. Estimation of diameter of cylindrical ligaments

Based on instability theory, it is clear that after the fluid film issued from the orifice, the main cause of atomization is mainly the surface wave instability. Due to the interaction with the gas medium, the wave amplitude grows until it gets to a critical point where the film begins to breakup into droplets in the form of a ribbon with half a wave length wide. As a result of the surface tension, these fragments are torn into ligaments that will subsequently disintegrate into droplets.

Weber *et al.* [2] suggested to estimate breakup wave number by

$$\lambda_{\max}^2 = 8\pi^2 a^2 \left(1 + \frac{3\mu}{\sqrt{2\rho_l a \sigma}}\right) = \frac{4\pi^2}{k_{\max}^2} \quad (28)$$

where $k_{\max}$ represents the wave number corresponding to the maximum growth rate:

$$k_{\max} d_L = \left(\frac{1}{2} + \frac{3\mu_l}{\sqrt{2\rho_l a \sigma}}\right)^{-\frac{1}{2}} \quad (29)$$

Considering the balance of mass, the relation between the drop size and the wave number is presented by

$$d_D^3 = \frac{3\pi d_L^2}{k_L}. \quad (30)$$

Substituting Eq. (30) for Eq. (31), it can be obtained as below:

$$d_D = \left(\frac{3\pi}{\sqrt{2}}\right)^{\frac{1}{3}} d_L \left(1 + \frac{3\mu_l}{\sqrt{2\rho_l a \sigma}}\right)^{\frac{1}{3}} \quad (31)$$

where d_L is the ligament diameter.

After simplification, it can be expressed as

$$d_D = 1.882 d_L (1 + 3Oh)^{\frac{1}{3}} \quad (32)$$

$$Oh = \frac{\mu_l}{\sqrt{2\rho_l a \sigma}}. \quad (33)$$

Previously Eq. (32) was used to predict the breakup of the Newtonian fluid film, however, to fully take the properties of non-Newtonian fluid into consideration, the shear rate estimated by Eq. (2) from Back *et al.* [24] was introduced into Oh number in this paper.

Eqs. (28) to (33) can be further combined to

$$d_L = 0.1837 \left[\left(\frac{8U_l}{a} \right)^{n-1} \right]^2 \quad (34)$$

which will be later used to estimate the breakup diameter of the ligaments.

4. Experimental Results and Analysis

4.1. The effect of injection pressure on breakup of film flow

Changing injection pressure (namely nozzle velocity or Re_n) would play a significant role in the breakup of film flow. Different morphology photographs for different injection pressures P_i are shown in Fig. 10. U_l satisfies the following correlation with P_i :

$$U_l = C \sqrt{\frac{P_i W_i L_i}{2(W_i + L_i) \rho g L}}. \quad (35)$$

From Fig. 10, it is obvious that as injection pressure increases, the film flow is broken up into more droplets instantly.

As shown in Figs. 11 and 12, the stripping breakup length decreases and spray angle increases substantially with the injection pressure which accelerates the disintegration of film flow. The curves of different ambient pressures in Figs. 11 and 12 demonstrate nearly identical trend, the distribution of which proves the positive effect of ambient pressure on breakup of film.

4.2. The influence of film thickness

The comparison of film flow depending on the film thickness is well reflected by Fig. 13. The film thickness is determined by the internal width of the orifice, and the change of film thickness plays a role in the vertical direction of the film.

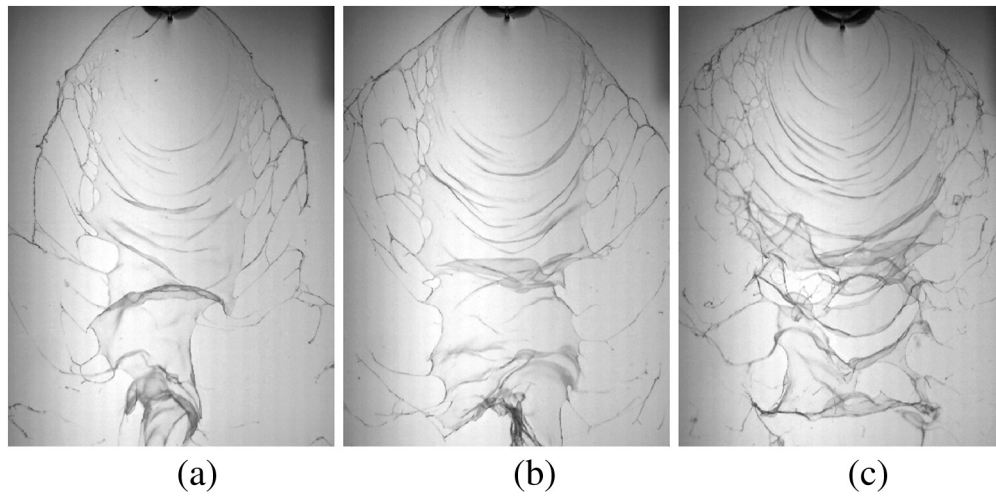


Fig. 10. Flow atomization morphology of simulant 2. (a) $P_1 = 2.5$ MPa, (b) $P_1 = 3.5$ MPa, (c) $P_1 = 4.5$ MPa.

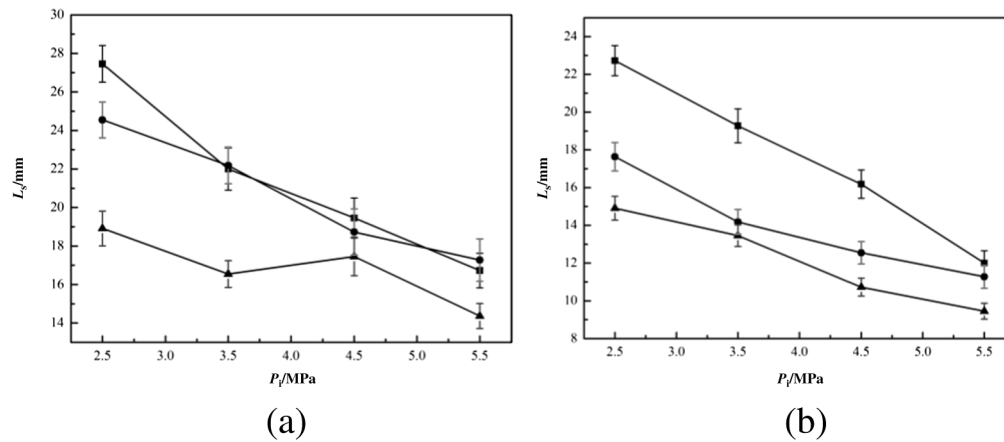


Fig. 11. Stripping breakup length as function of injection pressure, (a) simulant 1 and (b) simulant 2 ($T = 300$ K, $L_i = 2$ mm, $W_i = 0.3$ mm) ■ $P_a = 0.8$ MPa; ● $P_a = 1.2$ MPa; ▲ $P_a = 1.4$ MPa.

Fig. 14 presents the result of correlation about breakup morphology and film thickness. Fig. 14(a) shows that when the film thickness is varied from 0.3 mm to 0.7 mm, the stripping breakup length maintains a small length, and it is maximized when film thickness equals to 0.5 mm. Furthermore, Fig. 14(b) also predicts that when film thickness equals to 0.5 mm, the spray angles decrease to the minimum. Therefore, it can be

concluded that when a thickness of around 0.5 mm, the film is hard to atomize. According to Nasser Ashgriz [13], the increase of film thickness causes the increase of the viscous force that prevents the atomization when $L_t < 5$ mm, however, when L_t exceeds 5 mm, due to Eqs. (5) and (6), it is easier to break the force balance on the wavy film, that is why L_s decreases when $L_t > 5$ mm. According to Yang *et al.* [22], the maximum

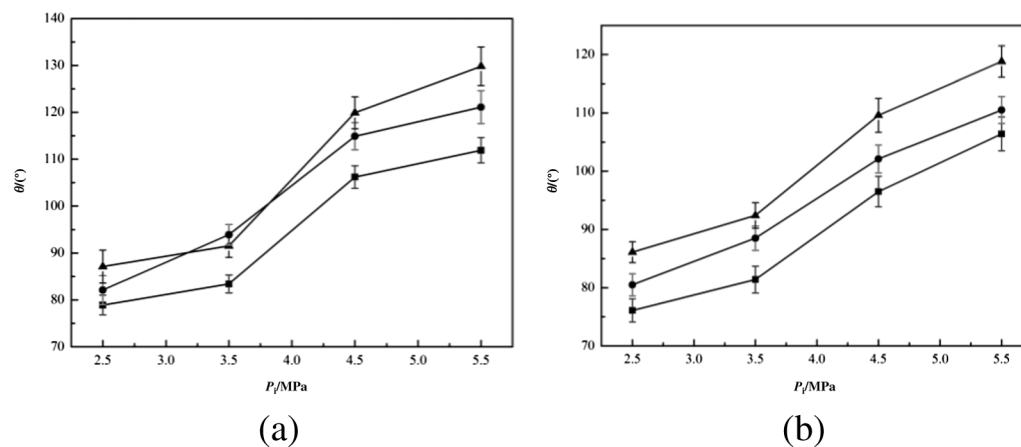


Fig. 12. Spray angles as function of injection pressure, (a) simulant 1 and (b) simulant 2 ($T = 300$ K, $L_i = 2$ mm, $W_i = 0.4$ mm) ■ $P_a = 0.8$ MPa; ● $P_a = 1.2$ MPa; ▲ $P_a = 1.4$ MPa.

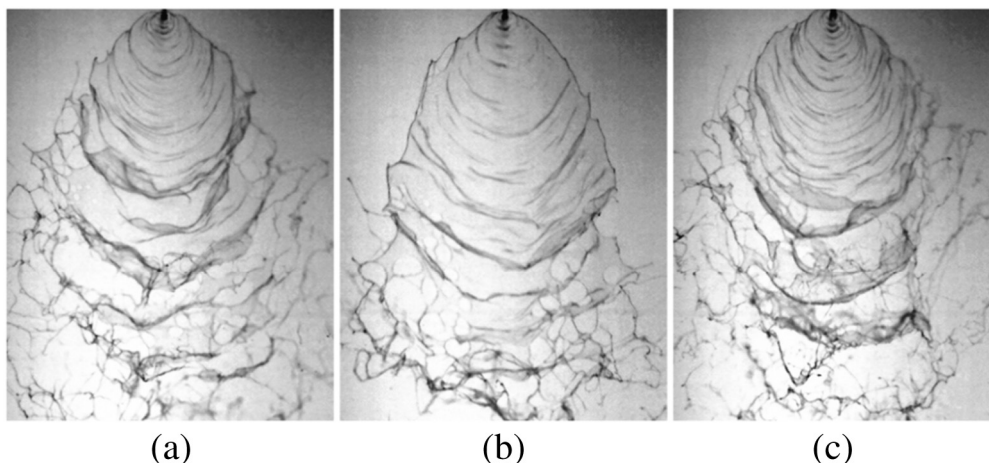


Fig. 13. Film atomization morphology of simulant 1, (a) $L_t = 0.3$ mm, (b) $L_t = 0.5$ mm, (c) $L_t = 0.7$ mm ($P_a = 1.0$ MPa, $P_i = 4.5$ MPa).

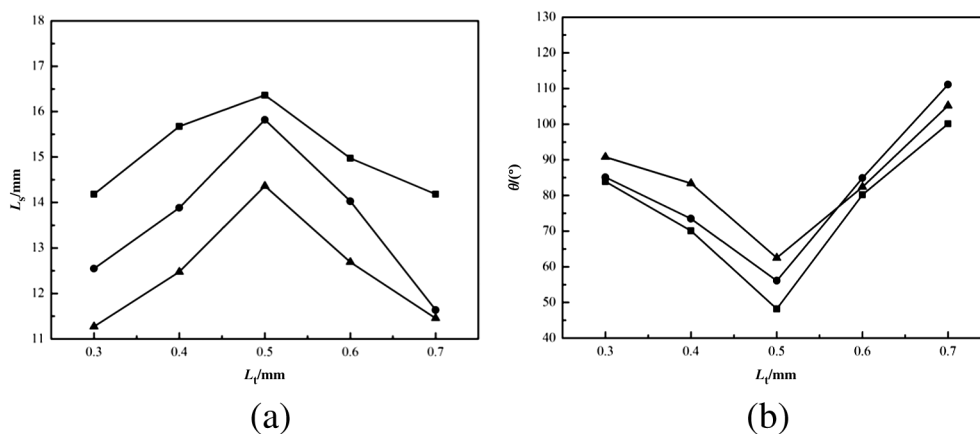


Fig. 14. (a) Stripping breakup lengths as function of film thickness, (b) spray angles as function of film thickness ($P_a = 1.0$ MPa, $T = 300$ K) ■ $P_i = 2.5$ MPa; ● $P_i = 3.5$ MPa; ▲ $P_i = 4.5$ MPa.

growth rate increases with the increase of film thickness which causes the disturbance waves to be more unstable. However, this doesn't mean that a thicker film help the film atomize for when film thickness increases, the dominant wave number decreases and the disturbance waves tend to develop into the direction of long wave. Therefore, the liquid film breaks up into thicker film ligaments that prevent the atomization. This point of view in the literature supports the present results well.

4.3. The effect of density ratio

The density ratio of gas to liquid, H , indicates the degree of the interaction between the film flow and ambient gas. Fig. 15 shows the effects of H on the instability of film flow under different conditions. The stripping breakup length in Fig. 15(b) is obviously shorter than that in Fig. 15(a) which illustrates when H increases, the aerodynamic interaction is more effective in inducing the breakup. The change of density ratio is realized by the variation of ambient pressure.

4.4. The effect of ambient pressure

The effect of ambient pressure is a combination of ρ_i and U_i . Through the conclusion drawn from above, the effect of ambient pressure is not a simple linear relation but a complex one. Fig. 16 represents simulant 1 film flow morphology based on the various ambient pressures in $P_a = 0.7, 1.0, 1.3$ MPa and the injection pressure maintains 4.5 MPa and ambient temperature 300 K.

From Fig. 16, it is shown that by increasing the ambient pressure the process of the breakup of film is not so drastic as with increasing injection pressure. Fig. 17 shows the development of stripping breakup lengths as ambient pressure. In proportion to the ambient pressure,

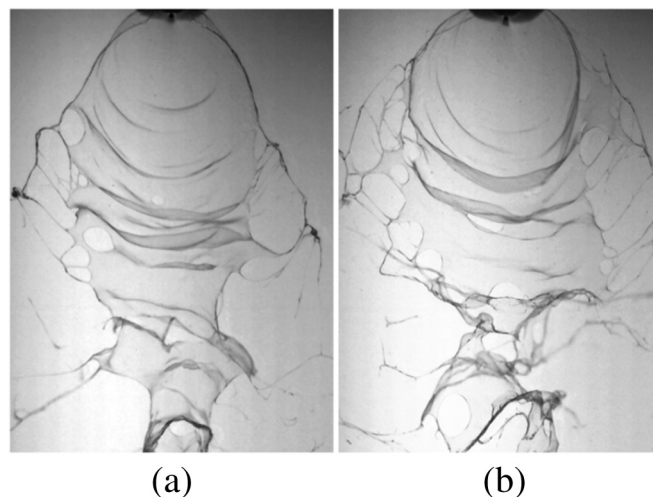


Fig. 15. Film atomization of different density ratio, $P_a = 1.0$ MPa, $P_i = 4.5$ MPa, $L_t = 0.5$ mm as constant, (a) $H = 0.00125$, (b) $H = 0.0062$.

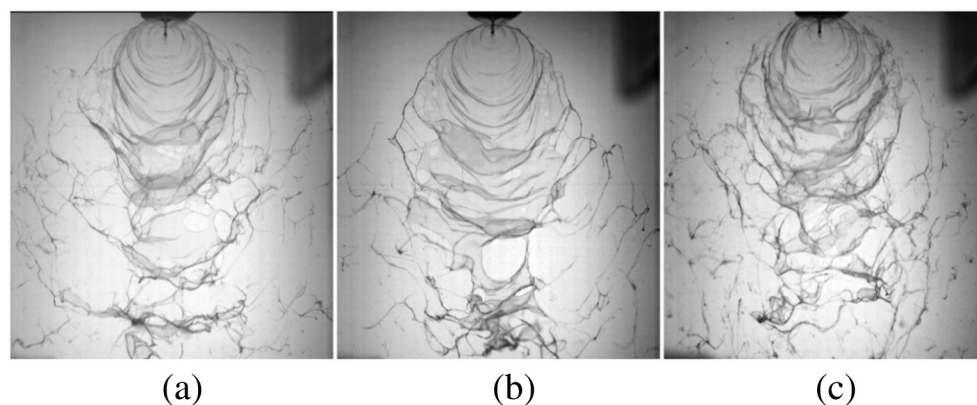


Fig. 16. Flow atomization morphology (a) $P_a = 0.7$ MPa, (b) $P_a = 1.0$ MPa, (c) $P_a = 1.3$ MPa.

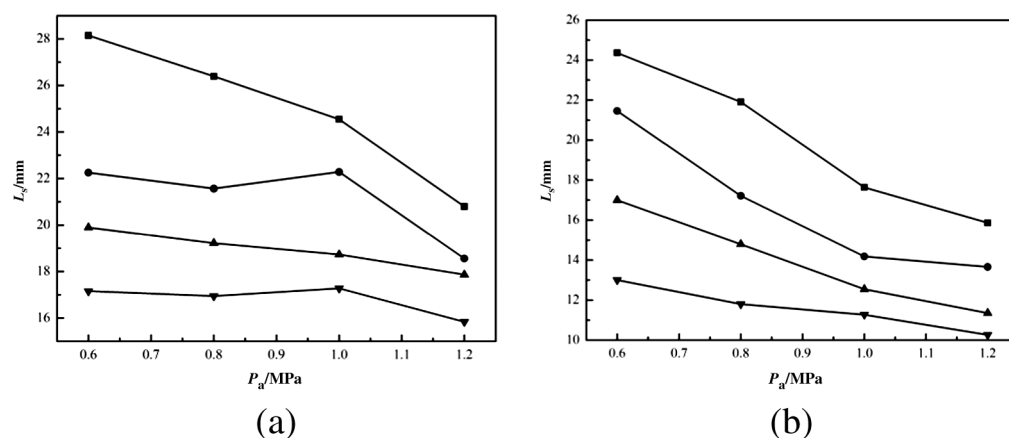


Fig. 17. Stripping breakup lengths as function of ambient pressure, (a) simulant 1 and (b) simulant 2 ($T = 300$ K, $L_i = 2$ mm, $W_i = 0.5$ mm,) ■ $P_i = 2.6$ MPa; ● $P_i = 3.5$ MPa; ▲ $P_i = 4.5$ MPa; ▼ $P_i = 5.5$ MPa.

the stripping breakup lengths decrease in most of the value range, which means that the increase of ambient pressure will definitely accelerate the atomization of film flow. Another side, increasing the ambient pressure leads to the increase of gas density.

5. Validation of the Theoretical Model

In order to verify the accuracy of the theoretical model, stripping breakup length is calculated according to Eq. (24) to compare with experimental results.

From Fig. 18(a) and (b), it can be known that the theoretical values coincide well both with the experimental values in the middle We region, and with York's theory in the whole We range. The predicted stripping breakup lengths are larger than the measured when $We < 250$, and the reason can be that the linear instability analysis is invalid to predict the breakup of film flows for the higher oscillation frequency. The property of the power law liquid causes the impediment of the atomization. As a result, the linear instability analysis is slightly disabled to predict the improvement of the disturbance in this specific narrow region. Generally speaking, the linear instability theory predicts the breakup characteristics well.

Fig. 18(c) shows the ligament diameters to the experimental data as function of injection velocity. When $U_l > 15 \text{ m} \cdot \text{s}^{-1}$, the calculated diameters show good agreement with experimental data. However, it underestimates the breakup diameters of the ligament when $U_l < 13 \text{ m} \cdot \text{s}^{-1}$. The complex physical property of power law liquid may lead to the discrepancies between the calculated and measured values. As a matter

of fact, the Oh number of non-Newtonian liquid is more complex than that defined in Eq. (28), which may cause some deviations. To sum up, the estimation for diameter of cylindrical ligaments put forward in this passage could still provide a good method to predict the breakup characteristic of film flow.

6. Conclusions

Experiment was carried out to study the breakup characteristic of power law liquid. The characteristic stripping breakup length and expansion angle were defined and extracted. It is clear that the stripping breakup lengths decrease while the expansion angles increase with the ambient pressure and the injection pressure.

Meanwhile, a linear instability analysis was adopted to predict the breakup characteristics of power law liquid where the effects of parameters such as flow index, Weber number, and density ratio on the maximum growth rate were analyzed, so that the predicting model of the stripping breakup length was put forward. Furthermore, the formula of ligament diameter was further derived with some simplification and modification, and a new correlation fully considering the properties of power law liquid was introduced to estimate the breakup parameter $\ln(\eta_b/\eta_0)$.

The present theory and those from the literature were compared with experiment by calculating the stripping breakup length and the diameter of the ligament. Although there exist some discrepancies between the present model and the measured values, the theoretical

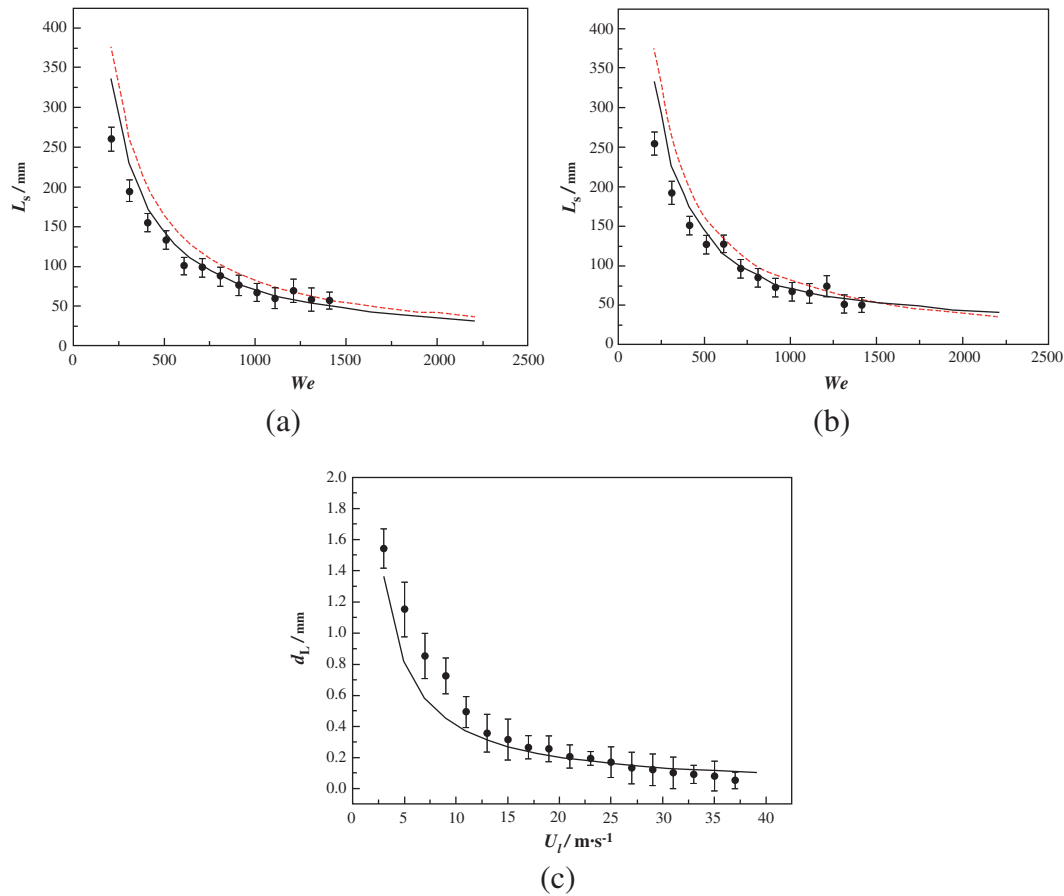


Fig. 18. (a) Stripping breakup lengths as function of Weber number for simulant 1, (b) stripping breakup lengths as function of Weber number for simulant 2, (c) diameter of the ligaments as function of the injection velocity for simulant 1 ($G = 0.000005$; $H = 0.006$; $\delta = 0.3$ mm; $K = 17.5$ Pa·sⁿ; $P_a = 0.9$ MPa). — the present theory; --- York's theory; ● experiment. Mean relative error (MRE) for (a) = 6.9 mm, MRE for (b) = 6.4 mm and for (c) = 0.13 mm.

linear instability can still be adopted to predict breakup characteristics of the power law liquid film.

Nomenclature

a	half thickness of the film, mm
D_l	diameter of a cylindrical ligament, mm
d	diameter, mm
F_i	inertial force, Pa
F_p	pressure force on the upper and lower surface, Pa
F_σ	force caused by the surface tension, Pa
F_μ	viscous force, Pa
H	density ratio of gas to liquid
K	consistency coefficient of non-Newtonian liquid, Pa·s ⁿ
k	wave number
L_s	stripping breakup length of liquid film, mm
L_b	breakup length of liquid film, mm
L_t	thickness of liquid film, mm
n	index of power law liquid
p	pressure, Pa
Re_n	generalized Reynold number ($Re_n = \rho_l U_0^{2-n} a^n / K$)
U	velocity of liquid film, m·s ⁻¹
We	Weber number ($We = \rho_l U_0^2 a / \sigma$)
δ	thickness of the sheet, mm
η_i	the fluctuation amplitude of the film surface, mm
γ	shear stress rate, m·s ⁻¹
θ	spray angle of liquid film, (°)
λ	wave length, mm
μ_l	fluid viscosity, Pa·s
ρ	the density of liquid or gas, kg·m ⁻³

σ	surface tension of liquid, N·m ⁻¹
τ_b	breakup time, s
φ	phase difference of adjacent liquid and gas, rad
ω	growth rate of surface wave

Subscripts

a	ambient
D	droplet
g	gas
i	injection
L	ligament
l	liquid
max	maximum
0	initial state

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