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Experimental study of jet surface structures and the influence of nozzle configuration

Chen Gong\textsuperscript{1,3}, Minguan Yang\textsuperscript{1}, Can Kang\textsuperscript{1} and Yuli Wang\textsuperscript{1,2}

\textsuperscript{1} School of Energy and Power Engineering, Jiangsu University, Zhenjiang, 212013, People’s Republic of China
\textsuperscript{2} Department of Mechanics, KTH-Royal Institute of Technology, Stockholm, SE-10044, Sweden

E-mail: chengong@ujs.edu.cn, mgyang@mail.ujs.edu.cn, kangcan@ujs.edu.cn and yuli@mech.kth.se

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Abstract
Under the three breakup regimes, the jet surface waves of different nozzles are captured and measured. The nozzles have different length to diameter ratios and contraction angles. The measured wavelengths are compared with the reported conclusions which were obtained by using spatial and temporal linear stability analysis. The results show that the jet wavelengths of different breakup regimes are covered by a single curve when the wavelengths are non-dimensionalized with boundary layer thickness. For the nozzle with equal length and diameter, the entire translation section starts at $Re = 3 \times 10^4$ and ends at $Re = 4.5 \times 10^4$. The wavelength non-dimensionalized with boundary layer thickness is independent of nozzle configuration. The ratio of initial wavelength to boundary layer thickness ranges from 2 to 4.

Keywords: high-speed liquid jet, surface wave, boundary layer, geometric parameters, breakup regime

1. Introduction

Many industrial processes and applications involve liquids as dispersed phases or sprays, rather than as continuous flows (Bayvel and Orzechowski 1993). Ejecting liquid into a gaseous environment is the most widely encountered liquid spray formation process. Deformations will appear on the liquid interface once the liquid flow issues from the nozzle,
and these deformations grow in space and time. In general, two major factors are supposed to control the primary atomization mechanism, namely, the presence of initial disturbances on the liquid–gas interface and a mechanism that allows some of these disturbances to develop and the breakup of the liquid flow occurs thereby. The primary atomization step has been generally ignored and atomization analyses have been devoted to establishing correlations between spray characteristics and selected parameters. In this context, efforts should be taken to study the primary atomization step, which serves as a vital link between the liquid emerging from the nozzle and the fully developed spray (Chigier 2005).

Theoretical analyses have been carried out on the initial distortion and disintegration of liquid streams (Lin and Reitz 1998, Sirignano and Mehring 2000). Relevant approaches are based on the determination of unstable waves that grow on the liquid–gas interface and therefore dominate its breakup. Nevertheless, the applications of these approaches have been limited so far. High-energy atomization processes are still untouched and little theoretical analysis has been reported about the coupling of the wave phenomenon with flow behavior in the nozzle.

Some researchers studied primary instability via numerical simulation. Representatively, Shinjo and Umemura (2010, 2011), Ménard et al (2007) and Takao (Yoshinaga and Kan 2006) have depicted the development of surface waves that lead to atomization and captured the ligaments and droplets from the disturbed liquid core surface. Numerical simulation requires initial and boundary conditions which are pre-determined by either stability analysis of different degrees of complexity or experimental measurements. The existing stability analysis cannot explain all the physical mechanism of the high-speed liquid jet.

Many researchers endeavored to study the development of surface wave using experimental methods. Yoshio (Morozumi and Fukai 2004) investigated the surface configuration of liquid jets using high-speed camera. With shadowgraph, Mayer (1994), (Mayer and Branam 2004) captured the surface waves and measured the wavelengths using traditional approaches. The pulsed photograph and holograph were used by Wu (Wu et al 1992, 1995, Wu and Faeth 1993, 1995) and Faeth (Faeth et al 1995) to observe breakup characteristics at jet surface, Sallam et al (2002) enriched the work of Wu and Faeth, and examined the breakup of the entire liquid column for turbulent liquid flows. In Hoyt and Taylor’s experiments (Hoyt and Taylor 1977a, 1977b), a relatively large nozzle was used and the backlight was employed. Jets with bright surface waves were produced. Moreover, surface wavelength measurement based on nine still jet images was provided and various stability analyses (Yoon and Heister 2003, Park 2005) were validated by wavelength. A set of experiments carried out by McCarthy and Molloy (1974) and the effects of nozzle configuration on the jet shape were studied. The aforementioned works served as a methodology basis for further research work.

The development of the jet surface wave is a reflection of the evolution of flow instability. Therefore, the study of surface wave is a crucial step towards well understanding the primary atomization. This paper presents a set of experiments involving six nozzles with different geometric parameters, each tested at jet velocities ranging from 10 to 40 m s−1. A spectral method is used to process the captured jet images. The experiments statistically characterize the axial instability wavelengths in the near-nozzle exit region of the liquid jet. The measured jet wavelengths for the six nozzles, at all flow velocities, are presented as a function of their axial locations. Furthermore, the relationship between jet surface wave and geometric parameters is investigated based on quantitative information extracted from jet images.
2. Experimental approach

2.1. Setup

Based on the linearized stability analysis (Brennen 1970), the boundary layer thickness of the jet at the nozzle exit is supposed to have a close connection with jet primary instability. There are two common types of the nozzle exit configurations. The nozzle has a parallel exit section, and the thickness of the boundary layer increases along the streamwise direction due to the wall and friction effects. The thickness of boundary layer can be calculated by the laminar Blasius solution:

$$\delta = 5 \sqrt{\frac{\nu L}{U}},$$

(1)

where $\delta$ is the thickness of the boundary layer. $L$ is the length of the nozzle parallel channel. $\nu$ is kinematic viscosity, $U$ is jet velocity.

The boundary layer thickness inside converging nozzle decreases along the streamwise direction due to the effects of the axial positive pressure gradient. The boundary layer thickness of the jet associated with this kind of nozzle can be calculated by the following equation (Pohlhausen 1921):

$$\delta = 3x \sqrt{\frac{U_r}{U}},$$

(2)

where $x$ is the distance between the sink and nozzle exit. $r$ is the radial distance from the nozzle symmetry axis. Here, $x = D/2 \sin \theta$, $r = D/2$. $D$ is the diameter of the nozzle exit and $\theta$ is the angle of the converging nozzle. Therefore

$$\delta = \frac{3}{2 \sin \theta} \sqrt{\frac{2D\nu}{U}}.$$  

(3)

According to equations (1) and (3), the nozzle geometrical parameters which can affect the thickness of boundary layer are length to diameter ratio ($L/D$) and the contraction angle ($\theta$). Two groups of nozzles were designed to identify the influence of nozzle geometrical parameters on jet surface structure. In the first group, the length to diameter ratio is considered. As shown in figure 1(a), in accordance with the work of Hoyt and Taylor (1977a, 1977b), the nozzle of Case 1 whose length to diameter ratio is equal to one was designed. The length to diameter ratio of Case 2 and Case 3 are 0.5 and 2, respectively. The nozzle contraction angle is considered in the second group. Maddahian’s et al (2011) work shows that the variation of contraction angle has significant effects on the axial boundary layer thickness while the angles range from 6° to 20°. Hence, the contraction angles of Case 4, Case 5 and Case 6 are set as 18°, 10° and 14° respectively. Detailed information of the nozzles is presented in table 1.

Figure 1(b) shows the experimental setup. Water is pumped from a container, the flow rate of the pump is controlled by gearing a variable-frequency drive, the jet velocity is changed accordingly. The fully developed inner turbulent flow is generated with the straight stainless steel pipe whose length-to-diameter ratio exceeds 40 (Faeth et al 1995). The length and inner diameter of the straight stainless steel pipe are 0.5 m and 8 mm, respectively. A rubber hose is used to connect the pump and the straight stainless steel pipe.

An OLYMPUS I-SPEED 3 high-speed camera in conjunction with a microscope was used to capture jet images. The exposure time of the camera was set as 1 $\mu$s in order to provide enough temporal resolution. For each experimental condition, a complete sampling
Figure 1. Components of the experimental system: (a) schematics of the nozzles with different length to diameter ratios \((L/D)\) and contraction angles \((\theta)\). (b) On-site image.

Table 1. Flow conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Length to diameter ratio ((L/D))</th>
<th>Contraction angle ((\theta))</th>
<th>Jet velocity ((m , s^{-1}))</th>
<th>Weber number (W_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>14°</td>
<td>12.4 24.4 32.9</td>
<td>7.6 29.7 53.9</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>14°</td>
<td>12.6 24.5 37.2</td>
<td>7.9 30.0 68.7</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>14°</td>
<td>12.0 24.2 33.9</td>
<td>7.2 29.3 57.2</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>18°</td>
<td>12.5 24.6 32.5</td>
<td>7.8 30.1 52.8</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>10°</td>
<td>12.7 25.3 32.3</td>
<td>8.0 32.0 51.9</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>14°</td>
<td>12.7 24.6 31.9</td>
<td>8.0 30.2 50.8</td>
</tr>
</tbody>
</table>
group consisted of 100 images. The size of the image was 1280 × 1024 pixels. The amplification of the microscope was set as 2.8 which provides a typical resolution about 6 μm/pixel. An OLYMPUS ILP-2 light source was used to produce bright light and the light is transmitted through an optical fiber with a diameter of 6 mm. Before arriving at the jet surface, the light beam passes through a 5 mm thick acrylic diffuser plate which was used to produce a uniform light distribution. The light, liquid jet and microscope are collinear.

Particle image velocimetry (PIV) was used to measure the jet velocity near the exit of nozzle. The PIV system consists mainly of a YAG200-NWL pulsed laser, a POWER-VIEW 4MP CCD camera and a micro-lens. The section of the jet near the nozzle exit is focused by using a micro-lens, and several groups of data that under the same experimental condition were measured. The average result of these data was used to reduce the random error. A WS-T11PRO digital thermometer with uncertainties of ±0.5 °C was used to measure water temperature, surface tension was determined accordingly.

For each kind of nozzles, we had conducted a series of experiments at different inlet pressures. And the velocities of these jets were measured too. According to the Chigier and Reitz (1996), Lin and Reitz (1998), the Weber number based on air density is calculated by:

\[
\text{We}_g = \frac{\rho_g U^2 D}{\sigma},
\]

where \(\rho_g\) is air density, \(\sigma\) denotes surface tension.

According to the Weber numbers calculated, the jets were divided into three successive groups, first wind-induced breakup regime, second wind-induced breakup regime and atomization regime. One typical case was selected from each group. These typical cases are denoted by subcases of a, b and c.

The flow parameters and physical properties in our experiment are presented in table 1.
2.2. Image processing

The basic idea of image processing is to measure jet surface wavelengths by processing the digital signals extracted from the jet images. Jet images are constructed based upon digital information representing image intensities. As shown in figure 2(a), a red line extends from the nozzle in the streamwise direction. The corresponding image intensity distribution along this line is presented in figure 2(b). Firstly, in the $X/D$ range of 0–0.8, the curve of the image intensities fluctuates violently but with small amplitudes. Compared with figure 2(a), it is easy to find that this part is corresponding to the smooth part of the jet. Then the curve has significantly changed near $X/D = 0.8$. The curve of this part has obvious periodicity. It has significantly large amplitudes and low frequencies compared to the former part. The streamwise lengths between adjacent wave crests are about 0.08 D which is equal to the distance of adjacent surface waves in figure 2(a). The development of the surface waves along the streamwise direction can be well represented by the image intensities. That is to say, the jet surface waves can be well measured by processing the digital signals extracted from the jet images.

The image processing method is presented here. Welch method, one of the commonly used digital signal processing methods (Mulgrew et al 2002) was selected. And the Blackmann window was used in image processing. The length of window is set as 0.5 D, corresponding pixel length is around 520. More detailed discussion about the selection of the digital signal processing method and important parameters (e.g. window function, length of window) could be found in our previous work (Gong et al 2016). Along the streamwise direction, a series of measurements were performed. The first sample was taken from the exit of the nozzle and the length of the sample was set equal to the window length. The measured result was set as the wavelength of the middle point of this sample. Then the second sample was taken from the position of 0.06 D, approximately 33 pixels, downstream of the nozzle exit. The length of the second sample was equal to that of the
first sample. The procedure was repeated until the end of the data set. To reduce the random error, 100 spanwise positions were measured with the same method, and then, other 99 jet images which were captured under the same experimental condition were processed by the same method. The average value of these 100 images was specified as the final wavelength.

3. Results and discussion

3.1. Wave structures

The surface waves of the jets under the three breakup regimes are presented in figure 3. The jet of Case 1a falls into the first wind-induced breakup regime. The surface structures of the jet are comparatively simple. In the streamwise range of $Y/D = 0–1.25$, there is no distinct wave structure on the jet surface. Meanwhile, the interface between the jet stream and ambient air is featured by straight lines, and the jet diameters are the same in this part. Then, a group of structures featured by periodic waves emerge at the streamwise position of $Y/D = 1.5$. Along the streamwise direction, these surface waves have similar configuration while the distances between two adjacent surface waves are about 0.1 D. Moreover, these waves are level and smooth in the spanwise direction.

The jet of Case 1b is compatible with the second wind-induced breakup regime. Similar to Case 1a, the jet of Case 1b also has a smooth part. However, the length of this part is only one third of the corresponding value of the Case 1a. Accordingly, the streamwise position where the periodic waves appear is much closer to the nozzle exit. At the same streamwise position, there are some clearly sine waves at the interface. Compared with Case 1a, the waves of second wind-induced breakup regime are complex. Besides large scale waves, there are also some smaller ones that emerge on the crest of the large waves. These smaller waves are so called secondary waves which correspond
to the secondary instabilities described theoretically by Landahl (1972). The amplification of the secondary waves and their interaction with the primary waves are supposed to result in the flow breakdown, turbulence formation and subsequent amplified disturbances.

As shown in Case 1c, under the atomization regime, the jet has a much shorter smooth part. The surface waves under this regime are significantly different from the aforementioned waves in size. The distance between adjacent surface waves is about 0.06 D, which is only half of the corresponding value for the jet of the first wind-induced breakup regime. As shown at the interface, the liquid ligaments appear and the jet is no longer steady.

The measured wavelengths are presented in figure 4. The wavelength along the streamwise direction experiences three parts, firstly it is smaller than 0.02, which is kept constant for a distance. After that, the wavelength dramatically increases with a slope about 0.2. Then the wavelength increases along the streamwise direction with a small slope of 0.05. Since the jet surface is unchanged in the range of \( Y/D = 0-0.8 \), this part can be treated as a kind of ‘stable state’. In this paper, this part is defined as ‘stable section’. The part where wavelength dramatically increases with a slope about 1 is defined as ‘transition section’, and the part where wavelength gradually increases with a small slope of 0.05 is defined as ‘unstable section’. Obviously, the length of stable section and the start wavelengths of the unstable section decrease with the Weber numbers. The unstable sections of the three breakup regimes show similar trends.

The reason that jet has a stable section is discussed. Boundary condition at the jet surface changes from no-slip to free surface boundary condition as the jet exits from the nozzle. The relaxation of the velocity profile of the liquid jet induces the instability of the jet surface. Meanwhile, the surface tension restrains jet surface deformation. The velocity of the jet surface is zero at the nozzle exit, which means the surface tension plays the leading role at this point compared with the inertial force. However, the effect of the surface tension attenuates as surface velocity increases. These explain why the jet has a part of smooth surface. Moreover, velocity gradients of boundary layer get higher as jet velocity increases. Therefore, the acceleration of jet surface velocity is increased. This may be one of the reasons underlying the

\[ \text{Figure 5. Variation of wavelengths with times and spanwise positions.} \]

\( Y \) direction represents the streamwise direction. \( Y = 0 \) corresponds to nozzle exit. The wavelengths and streamwise distance are nondimensionalized with respect to the nozzle diameter.
correspondence between the increase of jet velocity and the narrowed distance between the surface wave and the nozzle exit.

The reason that wavelength increase with $Y/D$ is explained here. Take the Case 1a of figure 4 for example, the reason that wavelengths increase in the transition section ($Y/D = 0.8–1.3$) and unstable section ($Y/D = 1.3–1.45$) are different.

Firstly, in the transition section ($Y/D = 0.8–1.3$), the sharp increase of wavelength is due to the increasing probability of jet surface translating from smooth to non-smooth with the increase of the streamwise distance. The comparison of single measured result with average result can make it easy to understand. As shown in figure 5, for the single measured result, the position that jet surface translates from stable section (wavelength is constant and smaller than 0.02 D) to unstable section (wavelengths are around 0.1 D) is a ‘streamwise point’. And the ‘streamwise point’ fluctuates in a certain range with the variation of time and spanwise position. The average wavelengths in figure 4 were obtained from 100 images (under the same experimental condition but different times), each providing 100 groups of data from various spanwise positions. In the average result, the ‘transition point’ transforms to ‘transition section’ ($Y/D = 0.8–1.3$ of Case 1a, in figure 4). Clearly, as the streamwise distance increases, the probability that jet surface translates from smooth part to non-smooth part is increased. Consequently, the average wavelength increases as well.

Secondly, in the unstable section ($Y/D = 1.3–1.45$), the increase of wavelength with streamwise distance is due to the relaxation of the velocity profile of the liquid jet and the acceleration of jet surface (Portillo et al 2011). The boundary condition at the liquid surface translates from a non-slip boundary condition to a free surface boundary as the jet exits the nozzle and this leads to the relaxation of the velocity profile of the liquid jet. In addition, the flow on jet surface accelerates near the nozzle exit, resulting in a positive axial strain rate, which stretches fluid elements in the streamwise direction and thus enlarges the wavelengths.

The effect of the jet velocity on the surface structures is discussed here. As it presented in figure 6, the jet with higher velocity has a thinner boundary layer. As a result, the inflection point is closer to the air–water interface and the scale of vortex is smaller. Accordingly, small-scale surface waves are supposed to be produced. This may partly explain why jet has small scale of surface waves under the atomization breakup regime.
3.2. Comparison with the theoretical results

A wave with frequency $f$ and velocity $U_j$ will have a wavelength $\lambda$, given by

$$\lambda = \frac{U_j}{f}. \quad (5)$$

The frequency obtained from Brennen’s stability analysis (Brennen 1970) is given by

$$f = \frac{\omega_r U_j}{2\pi \delta_2}, \quad (6)$$

where $U_j$ is the centerline velocity of the liquid jet. $\omega_r$ is the most unstable nondimensional frequency, the study of Brennen show that it equal to 0.177. $\delta_2$ is the boundary layer momentum thickness. A laminar boundary layer is assumed to begin in the straight section of the nozzle (Mattingly and Chang 1974, Hoyt and Taylor 1977a, 1977b, Portillo et al 2011). The momentum thickness $\delta_2$ at the exit of the nozzle is derived from the laminar Blasius solution for a flat plate:

$$\delta_2 = 0.664 \sqrt{\frac{\nu L}{U}}. \quad (7)$$

Therefore, substituting equation (6) into (5) gives the wavelength

$$\lambda = \frac{2\pi}{\omega_r} \left[ \frac{U_j}{U} \right] \delta_2 = \frac{2\pi}{\omega_r} U_j^* \delta_2. \quad (8)$$

Where $U_j^*$ is the nondimensional wave velocity base on jet velocity $U_j$.

The study of Brennen (1970) show that the nondimensional wave velocity $U_j^*$ deviates from unity. Jet surface waves develop from the disturbance with a frequency close to the most unstable mode of the system. Following Koch’s criterion (Koch 1985) for frequency selection, the most dominant frequency corresponds to the observed modes at the location of transition from absolutely unstable (AU) to convectively unstable (CU). For this particular frequency, $U_j^*$ equals 0.588 based on spatial analysis and 0.601 based on temporal analysis.

The medium in which the perturbation wave is traveling is being accelerated. As a result, this wave stretches as it moves downstream. Wavelength measurements of an arbitrary source wave of fixed frequency will, therefore, vary over streamwise locations. A Doppler-like analysis was made by Portillo and Blaisdell (2006). Let $u_w$ represent the wave speed relative to a fixed lab frame of reference, $u'_w$ the wave speed relative to the local fluid, $U_s$ is the surface’s edge (medium) velocity which can be obtained from Goldstein’s (1933) analysis. $x_m$ is an arbitrary streamwise location where measurements are made, $x_s$ is the location where the wave is generated (AU/CU transition location in this analysis) and assuming the wave travels at a constant velocity in the fluid, that is, $u'_w$ is constant. Then

$$u'_w = u_w(x_s) - U_s(x_s) = u_w(x_m) - U_s(x_m), \quad (9)$$

$$u_w(x_m) = u_w(x_s) - U_s(x_s) + U_s(x_m). \quad (10)$$

It is well known that for a fixed source in a moving medium, the frequency remains unchanged (Thornton et al 1996) with the movement of the medium. With this in mind, a measured wavelength can be obtained:

$$\lambda_m = \frac{u_w(x_m)}{f} = \frac{u_w(x_s) - U_s(x_s) + U_s(x_m)}{f}. \quad (11)$$
Rearranging equation (11) and defining $\lambda_\omega = u_\omega(x_\omega)/f$, then

$$\lambda_m = \frac{\lambda_\omega}{1 + \frac{U_k(x_m) - U_k(x_\omega)}{u_\omega(x_\omega)}}.$$  \hspace{1cm} (12)

Based on the analysis of equations (5), (6) and (8),

$$\lambda_t = \frac{2\pi}{\omega_t} U_\omega^* \delta_2.$$  \hspace{1cm} (13)

Substituting equations (13) into (12) gives the most unstable dimensional wavelength predicted from linear stability analysis:

$$\lambda_m = \frac{2\pi}{\omega_t} U_\omega^* \delta_2 \left[ 1 + \frac{U_k(x_m) - U_k(x_\omega)}{u_\omega(x_\omega)} \right]$$

$$= \frac{2\pi}{\alpha_t} \left[ 1 + \frac{U_k(x_m) - U_k(x_\omega)}{u_\omega(x_\omega)} \right] \delta_2,$$  \hspace{1cm} (14)

Where $\alpha_t$ is the wavenumber, $\alpha_t = \omega_t / U_\omega^*$.

The comparison of wavelengths is presented in figure 7. Based on the analysis of Goldstein, the edge velocity is zero at the separation point and it is expected to accelerate as it moves downstream. Accordingly, the theoretical wavelength rapidly increases from the nozzle exit. Within a very short streamwise distance, non-dimensional theoretical wavelength increases to 30, and then the growth rate decreases dramatically and tends to zero along the streamwise direction.

The measured wavelengths of the transition section and unstable section have variation trends similar to theoretical results. However, the experiment results show that the jet has a smooth part and the wavelengths rapidly increase at the end of the smooth part. For Case 1a and Case 1b, the experimental data are smaller than both the spatial and temporal theoretical
results. The experimental results of Case 1c are partly between spatial and temporal theoretical wavelengths.

As presented in figure 8, data of all the three breakup regimes collapse to a single curve as measured wavelengths are non-dimensionalized with the boundary layer thickness and plotted against a stretched axial coordinate. Stretching is accomplished by multiplying streamwise distance \( Y \) by the jet velocity \( U \). As shown in figure 7, the slope of the transition section is about 10 times the corresponding value of the unstable section.

Since viscosity remains constant in these experiments, the scaling can be converted to non-dimensional parameters, that is, the streamwise axis becomes

\[
U \cdot Y \sim \frac{U \cdot Y}{\nu} = \text{Re}_Y.
\]

Clearly, for the jet of Case 1, the transition from stable section to unstable section starts at \( \text{Re}_Y = 3 \times 10^4 \) and ends at \( \text{Re}_Y = 4.5 \times 10^4 \).

3.3. The effect of length to diameter ratio

Figure 9 shows nozzles with various length to diameter ratios and corresponding jet images and measured wavelengths. Under the three breakup regimes, the jet images of the three nozzles are presented in figure 9(b). The jet surface of all the experimental condition experiences a smooth part and periodic surface wave part. Compared with the Weber numbers, the length to diameter ratio of the nozzle has little effect on the length of the smooth part. However, under the same breakup regime, the configuration and streamwise scale of the surface waves vary with the length to diameter ratio.

The measured wavelengths of the jets are presented in figure 9(c). The length to diameter ratio has little effect on the wavelength of stable section but significant effect on the wavelength of transition section and unstable section. The jet that was produced by a longer length...
Figure 9. Nozzles with different length to diameter ratios and corresponding jet images and wavelengths. (a) Nozzle configurations. (b) Jet images. (c) Measured wavelengths. These three nozzles have the same contraction angle of $14^\circ$, and the length to diameter ratios are 1, 0.5 and 2, respectively. Case a, b and c correspond to first-wind induced breakup regime, second-wind induced breakup regime and atomization breakup regime.
to diameter ratio nozzle is supposed to have a thicker of boundary layer at the nozzle exit. As a result, the wavelength of unstable section of this jet is larger than others. The variation of wavelengths in transition section depends on the curvature and scale of surface wave (Gong et al 2016). This may partly explain why the wavelength of transition section of the curve varies with length to diameter ratio.

Wavelengths non-dimensionalized with the boundary layer thickness are presented in figure 10. The wavelengths in the unstable section of different length to diameter ratios tend
to be collinear. Meanwhile, the wavelengths of transition section are also show little difference. Clearly, wavelength of the unstable section can be scaled by the thickness of boundary layer and Case 1, 2 and 3 have similar velocity profiles at the nozzle exit.

3.4. The effect of contraction angle

The configuration of the nozzle with different contraction angles are presented in figure 11(a). The boundary layer thickness increases in the region near the nozzle inlet due to gradual penetration of friction effects into the flow. However, because of the effects of the axial pressure gradients, boundary layer thickness will decrease further in the streamwise direction. According to equation (3), boundary layer thickness is inversely proportional to the sine of contraction angle.

As shown in figure 11(b), nozzle contraction angle also has remarkable effect on jet surface structure. Similar to figure 9(b), the formation and streamwise scale of the surface waves of figure 11(b) also vary with contraction angle. More importantly, the streamwise position where the surface wave appears is also sensitive to nozzle contraction angle.

The measured wavelengths in figure 11(c) show that contraction angle not only affects the wavelength of transition section and unstable section, but also has an effect on the streamwise position where the transition starts. The nozzles in figure 11(a) have different inlet
Figure 11. Nozzle with different contraction angle nozzles and corresponding jet images and wavelengths. (a) Nozzle configurations. (b) Jet images. (c) Measured wavelengths. The length to diameter ratio of these nozzles are equal to zero, and the contraction angles are 18°, 10° and 14° respectively. Case a, b and c correspond to first-wind induced breakup regime, second-wind induced breakup regime and atomization breakup regime.
angles and lengths of inner wall which have significant effects on the flow inside the nozzle. Hence, the velocity profiles at the nozzle exit are quite different for the three nozzles, as leads to unequal lengths of the stable sections.

Similar to figure 10, the wavelengths at different contraction angles are non-dimensionalized by boundary layer thickness, as shown in figure 12. It is seen that the wavelength of
the unstable section also tends to be collinear. However, the ratio of the wavelength to the thickness of the boundary layer is obviously smaller than that in Figure 10. Since the nozzles of Case 4, 5 and 6 have no straight section, the velocity profiles at the nozzle exit are quite different from the Case 1, 2 and 3. Moreover, the laminar boundary layer thickness of Case 1, 2 and 3 were assumed to begin in the straight section of the nozzle. These may partly explain the difference between Figures 10 and 12. However, these do not affect the collinear tendency of the wavelength points of the unstable section.

4. Conclusion

The jet surface structures of six nozzles with different length to diameter ratios and contraction angles are captured and measured. And the measured results are compared with the theoretical results. The main conclusions are as follow:

(1) In the region near the nozzle exit, jet surface is featured by a smooth part before it is destabilized and enters the unstable section afterwards. The position where jet surface translates from stable to unstable approaches the nozzle exit as jet velocity increases. However, the variation trend of the wavelength of the transition section in streamwise direction is insensitive to the jet velocity.
Experimentally obtained wavelengths of transition section and unstable section are similar to the linear stability analysis results. The jet wavelengths of different breakup regimes are covered by a single curve provided that the wavelength is non-dimensionalized with boundary layer thickness. For the nozzle with equal length and diameter, the entire translation section starts at $Re_Y = 3 \times 10^4$ and ends at $Re_Y = 4.5 \times 10^4$.

The wavelength scale of the unstable section hinges on the scale and location of the vortices inside the jet boundary layer. The wavelength non-dimensionalized with boundary layer thickness is independent of nozzle configuration. The ratio of initial wavelength to boundary layer thickness ranges from 2 to 4.

Acknowledgments

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