Experimental Investigation of Flow and Coherent Properties of Excited Non-Circular Liquid Jets

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ABSTRACT

Non-circular jet is identified as an efficient passive flow-control technique that attracts many research topics. The existence of twine-vortexes is the main reason for dissimilarity between circular and non-circular jets. Which also influences the production of droplets and satellites as well as the jet instability. This investigation presents instability analysis of liquid-gas interface as an applicable conception in free-jet flows. We experiment different jet geometries within a gas ambient in order to study their hydrodynamic behavior. These studies give an appropriate perception about contributing forces that play essential roles in fluid instability. We focus on varying viscosity and surface tension as our excitation techniques. These methods are vital to examine the key properties of non-circular jets such as breakup and decay length, axis-switching wavelength as well as produced droplets and satellites characteristics. First, instabilities of charged liquid jets are investigated by considering the interaction between electric and inertial forces. Also, the viscosity effect was studied for its interaction with the inertial and surface tension forces. In each case, liquid jet in-stability for various nozzle geometries over a specific range of jet velocity is examined. The obtained results illustrate that the geometry of nozzle has an important effect on jet instability. In addition, by increment of We number, the breakup and decay length as well as the axis-switching wavelength are raising. However, by the rise of twin-vortex number, the breakup length increases but the decay length and axis-switching wavelength decrease.

Keywords: Non-circular Free jet; Liquid-gas instability; Axis-switching; Breakup length; Penetration length.

1. INTRODUCTION

Fluid science has provided uncountable excellences in manufacturing and science. However, developing our knowledge about fundamental jet behavior would help to create new branches in this field. Non-circular jets are identified as an efficient method of passive flow control that improves the performance of various practical systems significantly. That also comes with relatively low cost where jet performance relies solely on changes in nozzle geometry.

Jet stability and hydrodynamical parameters of fluid are influenced directly by the nozzle cross-section geometry. Non-circular nozzle shapes have different effects on instabilities of jet interface in comparison to the circular one. They can be applied in the process of mixing subsonic and supersonic jets Gutmark et al. (1990), Wlezien and Kibens (1988), Tam and Burton (1984). They also increase the efficiency of combustion engines by decreasing breakup length of the jet which converts fuel into minuscule droplets and raises the chemical reactions Gutmark et al. (1989). From the heat transfer point of view, instabilities on the jet surface besides changing the flow patterns will also enhance the heat transfer Ho and Gutmark (1987). Light metal powders can be manufactured by cooling dielectric liquids, where formation of the particles requires precise studies on jet instabilities under the effect of lateral electrical field Kandjani et al. (2010), Khoshnevis et al. (2014). Another remarkable application of jet flow is spray drift of pesticides in the agricultural field Nuyttens et al. (2010), Nuyttens et al. (2006).

The flow patterns associated with non-circular jets include vortex evolution and interaction mechanisms, as well as flow instabilities and fine-scale turbulence augmentation. Also, a general nozzle geometry comparison for elliptical, triangular and quadrangular cross-sections has been analyzed by different researches Reeder and Samimy (1996), Baty and Morris (1995). One of the earliest stud-ies
on non-circular jet stability and their application to manipulate jet-mixing behavior was carried out by Crighton (1973). Rayleigh (1879) as a pioneer gave a theoretical description for non-circular jets. He studied a cylinder of incompressible in-viscid liquid with an undulating jet cross section which had infinitesimal amplitudes. Recently, Rajesh et al. (2016) has presented an experimental study on the wavelength and oscillation amplitude of non-circular jets discharging from elliptical, triangular and square nozzles.

Considering Fig. 1, the main difference between non-circular jet instabilities and circular one is in the existence of twin-vortexes in corners of triangular and quadrangular jets, and also in segments of maximum curvatures in the elliptical jet. Twin-vortexes numbers are zero, two, three and four in circle, elliptic, triangle and quadrangle jets respectively. Mentioned vortexes had been perceived experimentally by flow visualization, Reeder and Samimy (1996), Zaman et al. (1994). These twin-vortexes change the geometry of liquid-gas interface. Subsequently, contraction and expansion of the interface will be in the central axis of the jet in contrast to the circular one. For the case of the elliptical nozzle, it is easy to observe the twin-vortexes since it is two dimensional. On the other hand, for the other cases with corners, effects of vortexes are three-dimensional that cannot be easily detected. Axis-switching occurs at the beginning -- limited length --of the jet and then gradually turns to normal waves.

Stability theory shows the effects of initial momentum, aspect ratio and radius of curvature on the initial flow evolution. For example, the sensitivity of elliptic jets towards the distribution and relevant momentum thickness is observed in Schadow et al. (1987), Quinn (1989), and Lee and Baek (1994). It was discovered that the occurrence of axis-switching, its locations and entrainment rates change by different aspect ratios of elliptical jets.

In recent years, different scholars have studied elliptical liquid jets in order to understand the jet instability and breakup behavior at different operational conditions Kasyap et al. (2008), Amini and Dolatabadi (2011), Amini et al. (2014), Muthukumar and Vaidyanathan (2014), Sharma and Fang (2014), Sharma and Fang (2015), Wang and Fang (2015). Different jet breakup modes are depicted in Fig. 2 where break up length is plotted verses jet velocity. For low velocities, continues flow
of jet is not formed, and droplets are constructed in
stantly on nozzle’s outlet which is called dripping
mode. As the velocity increases, axisymmetric
waves form on the interface till achieving the apex
known as capillary break up. After Dripping until the
maximum break up length (umax), the domain is
determined axisymmetric flow. By increasing jet
velocity, three-dimensional flow mode commences
(see Fig. 2) wherein asymmetric waves are formed.
Also, an atomization mode appears by approaching
larger velocities Kitamura et al. (1982).

Imposing harmonic disturbance to the jet surface is
mandatory, to investigate the instability of jet
column. From this perspective, growing disturbance
rate influences jet parameters directly e.g., breakup
length, frequency of the interface waves and
formation of droplets and satellites. A theory known
as growth rate of developing disturbance is
elaborated in Kitamura et al. (1982), Ashgriz (2011),
which investigated the size of droplets and satellites
produced from following disturbances:

- Utilizing acoustic waves on the interface of jet,
- Applying high voltage electric field via
  generating alternative contraction and expansion,
- Imposing oscillated flow,
- Enforcing periodic heaters,
- Changing the surface tension of the liquid jet.

Jet velocity and wavelength of disturbance are the
main factors for droplets and satellites formation. As
it is depicted in Fig.3 for high velocity jet, both
droplets and satellites are formed. In contrast, for low
velocity jet and high frequent disturbance, only
droplets are formed. Electric field influences on
instability of jet and formation of droplets are studied in
Khoshevis et al. (2012), Hokmabad et al. (2014). In an experimental work,
Tabatabaee-Hosseini et al. (2012) studied the
colliding of two opposing jets under the same angle
in the presence of electric field.

In this paper, nozzle geometry effects on excited
liquid jets are investigated. Among possible
asymmetric shapes, elliptic, equilateral triangular
and quadrangular nozzles are selected. Geometrically,
these jets are considered as the cases which clarify the effect of nozzle
configuration on the flow behavior. By using these
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nozzles, which makes it possible to analyze the
effects of corners (segments of greater curvature)
on the instability of jet.

Fig. 3. a) Formation of only droplets due to
uniform breakup of liquid jet column with low
velocity and high frequent disturbance, b)
formation of droplets and satellites
simultaneously, due to unstable liquid column jet
with high velocity and low frequent disturbance.

Charge induction is a suitable approach to change
the liquid jet surface tension. The electrostatic
repulsive force caused by free charges on the jet
surface tends to decrease the liquid surface tension
that yields a sooner jet break-up in comparison to
uncharged models. This related technique is
widely applied to electrostatic spray Cloupeau and
Prunet-Foch (1990) for industrial and agricultural
purposes. The theoretical work was pioneered by
Rayleigh (1882), who developed a theory of
stability for electrified inviscid jets—subjected to
disturbances of infinite wavelength—flowing in
vacuum region. Basset (1894) studied the stability of
axisymmetric disturbances on charged Newtonian jets under the effects of viscosity and
the ambient gas. Later, Taylor (1969) corrected
errors of Bas-set analysis. Schneider et al. (1967)
experimentally verified the axisymmetric
theoretical results by observing the breakup of a
charged water jet through a grounded cylindrical
electrode. Huebner (1969) also conducted a series
of experiments on charged water jets. This study
showed that increasing the amount of electricity
enhances the growth of sinuous non-axisymmetric
disturbances Numerical simulations describe
details of vorticity dynamics and clarified its
mechanisms as well as effects of heat transfer on
behaviour of non-circular jets. Koshigoe and Tubis
(1986), Koshigoe and Tubis (1987), Koshigoe et al.
(1988) analyzed the instability of jets with
general shape and proposed a Greens function
technique and a generalized shooting method.
Recent studies of Kasyap et al. (2009) showed that
a liquid jet emanating from an elliptic nozzle
exhibits more unstable behavior or a faster breakup
than a corresponding circular liquid jet.
Furthermore, they found that decreasing aspect
ratio (ratio of minor to major axis) of the elliptic
nozzle in some ranges makes the elliptic liquid jet
more unstable. Instability of an inviscid elliptic
liquid jet in an inviscid gas has been investigated
analytically by Dityakin (1954). By neglecting the
gravity effects and considering the gas density, a 3-
D temporal dispersion equation was derived. Later
on, Bechtel et al. (1988) developed a one-
dimensional model for slender viscoelastic elliptic
liquid jets and used the predicted axis-switching
behavior to measure dynamic surface tension and
elongational viscosity of fluids. In a subsequent
article, Bechtel (1989) studied viscosity and
gravity effects on an elliptic jet in detail.

Charged jet is another way to change the
surface tension. Electrostatic charge is
applied to the surface of liquid jet through
grounded nozzle or applied electrodes. This
method has been done on charged water jet
in electrostatic spray. These ions induce electric
field in the neighborhood of jet surface and
furthermore influence the oscillation of surface
tension. This can be modeled by following
equation:

\[ \sigma_{\text{eff}} = \sigma_0 + \Delta \sigma \times \cos(\omega t) \]

where \( \sigma_{\text{eff}} \) is the effective surface tension,
\( \sigma_0 \) is the initial surface tension,
\( \Delta \sigma \) is the amplitude of oscillation,
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2. PHYSICS OF THE PROBLEM AND GOVERNING EQUATIONS

In addition to the main equations, it is suggested to benefit auxiliary equations originated from the physics of experimental investigation. Hence, the Navier-Stokes equations for this case are as follows:

\[ \nabla \vec{V} = 0 \]  
(1)

\[ \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{u} + g + \vec{F} \]  
(2)

Eqs. (1)-(2) represent continuity and momentum equations, respectively. In these equations, \( u, P, \nu, g \) and \( F \) demonstrate velocity component in direction of jet flow, pressure inside the fluid, kinematic viscosity of the flow, density, acceleration of gravity and other body forces caused by external fields in the given order.

By utilizing necessary scales for variables and excluding the hydrodynamical forces where other body forces are ignored, non-dimensional numbers are proposed as:

\[ \text{Re} = \frac{\rho D_h U}{\mu}, \text{We} = \frac{\rho D_h U^2}{\sigma}, \text{Fr} = \frac{U^2}{g D_h} \]  
(3)

\( \text{Re}, \text{We} \) and \( \text{Fr} \) indicate Reynolds, Weber and Froude numbers in liquid jet which represent buoyancy, surface tension and gravity forces, respectively. Tension balance for liquid-gas interface has a great influence on jet instability which is defined:

\[ (P_j - P_j + \sigma_{j-j}, K) \hat{n} = (\tau_j - \tau_i) \hat{m} \]  
(4)

where \( \tau, \hat{n} \rightarrow, \sigma_{j-j} \) and \( K \) show stress tensor, unit normal vector on interface, surface tension in interface and mean curvature factor of jet’s surface. In order to obtain \( \sigma_{j-j} \) and \( K \), following equations are proposed:

\[ \sigma_{j-j} = \sigma_j + \sigma_s - 2 \sqrt{\sigma_j \sigma_s} \]  
(5)

\[ K = \frac{1}{R_1} + \frac{1}{R_2} \]  
(6)

where \( \sigma \) and \( \sigma_s \) are the surface tension of the jet and base flows and \( R_1 \) and \( R_2 \) are radii of the jet’s cross section curvature.

To illustrate all effects of instability based on mean values and their disturbances, we use:

\[ u = \bar{u} + u', v = \bar{v} + v', p = \bar{p} + p', R = a + \xi \]  
(7)

where \( u \) and \( v \) are in the longitudinal and radial jet velocity, \( p \) is jet pressure, \( a \) is the mean radius and \( \xi \) is the disturbance of mean radius caused by instability. Eq. (7) rely on time because the disturbances of instabilities (prime variables) are time-dependent. Note that mean values do not depend on time. By utilizing the values of Eq. (7) and revising continuity and Navier-Stokes equations, non-linear equations can be written as linear ones in cylindrical coordinate as:

\[ \frac{1}{r} \frac{\partial \bar{v}}{\partial r} + \frac{\partial \bar{u}}{\partial x} = 0, \frac{\partial \bar{u}}{\partial x} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial x}, \frac{\partial \bar{v}}{\partial x} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial r} \]  
(8)

Eqs. (8) can be solved by means of analytical methods which leads to jet surface curvature equations in terms of its disturbance Das (1997):

\[ \frac{1}{R_1} = 1 + \frac{\xi}{a}, \frac{1}{R_2} = \frac{-\xi_{\text{ext}}}{(1 + \xi_{\text{ext}}) \eta^2} \]  
(9)

here, \( \xi_{\text{ext}} \) shows jet interface function and \( \xi_{\text{ext}} \) depicts the interface curvature function of main direction of jet. According to the Eqs. (9), non-linear time-dependent liquid flow pattern can be analytically solved in particular circumstances for the circular nozzle. This pattern fails to be used for non-circular jets, therefore, they do not have any specific analytical solution. On the other hand, for non-circular jets, the theoretical jet cross section is given in polar coordinate by Rayleigh (1879). In order to find the radial distance of the jet, we have:

\[ R = a_0 + a_0 \cos n \theta \]  
(10)

where \( a_0 \) and \( a_0 \) are the angular coordinate, the mean radius of jet and amplitude of the instability.

The wavelength of jet oscillation is written as follow:

\[ \lambda = \frac{2\pi U}{p} \]  
(11)

where \( p \) is the thermal frequency of jet instability.

By assuming that an is diminutive comparing to \( \alpha_0 \), the non-dimensionalized wavelength of jet instability for non-circular jets is calculated as below Kasyap et al. (2009), Amini and Dolatabadi (2012), Wang and Fang (2015):

\[ \frac{\lambda}{D} = \frac{\pi \text{We}^{0.5}}{\sqrt{2(n^3 - n)}} \]  
(12)

In this equation \( n \) is the number of undulations in the cross section of the jet which is 2, 3, and 4 for elliptical, triangular and square jets, respectively.

3. EXPERIMENTAL SETUPS

Non-circular jets are highly significant due to producing instabilities originated from contracting and expanding jet interface as well as satellites and droplets creation. Ho and Gutmark (1987), Baty and Morris (1995) have depicted the notable application of these jets.

In order to study the nozzle geometry, four sets of stainless steel nozzles with different geometries and approximately same cross sectional areas were manufactured (by a wire-cut electro discharge machining process) and tested (see Fig. 4). The geometric details of the nozzles are given in Table 1. The Hydraulic diameter of the nozzles, \( D_h \) is estimated as \( D_h = 4A/P \), that \( A \) is nozzle exit area and \( P \) is wetted perimeter.
Experiments were carried out with distilled water for the first method of excitation (charged jet). While in the second method of excitation, different fluid solutions of water-glycerol mixture were utilized to generate viscosity variations. In Table 2, physical properties of operating fluids are shown. For calculating $\sigma_{\text{mix}}$ (surface tension of mixture) in water-glycerol with different solutions, we use following equation:

$$
\sigma_{\text{mix}} = \phi \sigma_w + (1 - \phi) \sigma_{\text{Gl}}
$$

(13)

where $\Phi$ is volume fraction of solution and other subscriptions of $\sigma$ represent water (w) and glycerol (Gl).

A setup (see Fig. 4) is designed in a way that jet flow will be in a steady state. During experiments, nozzles are fixed in a feed tank with 50 mm diameter and 300 mm length to supply the essential hydrostatic back pressure. First, liquid flows appropriate to the output jet velocity and reaches the constant height in head tank ($h_0$). Then, for controlling feed tank’s head ($h_1$), it overflows from the head tank to the main tank. A control valve is used to supply experimental fluids from the head tank to the feed tank to create jet flow with adequate quantity of velocity.

In the present work, jet velocity is computed via two measurement methods; The first one is direct discharge using sampler tank (sampling by time) and the second one is the flow rate considering the flow motion continuity with nozzles cross sections area. By stabilizing head of feed tank ($h_1$) and applying Torricelli’s equation, output velocity is calculated by:

$$
U_j = \sqrt{2gh_1}
$$

(14)

The experiments are performed in two different sections. In the first part, the behavior of non-circular charged water jets are studied; and in the second part,
Fig. 5. Camera views for non-circular nozzles.

Table 2 Physical properties of working fluids

<table>
<thead>
<tr>
<th>Utilized fluids</th>
<th>( \rho (\text{kg/m}^3) )</th>
<th>( \mu (\text{kg/(m\cdot s)}) )</th>
<th>( \sigma (\text{N/m}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>998</td>
<td>( 8 \times 10^{-4} )</td>
<td>0.073</td>
</tr>
<tr>
<td>GL1(70% water+30% glycerol)</td>
<td>1068</td>
<td>( 1.87 \times 10^{-3} )</td>
<td>0.070</td>
</tr>
<tr>
<td>GL2(50% water+50% glycerol)</td>
<td>1121</td>
<td>( 4.21 \times 10^{-3} )</td>
<td>0.069</td>
</tr>
<tr>
<td>GL3(30% water+70% glycerol)</td>
<td>1176</td>
<td>( 14.1 \times 10^{-3} )</td>
<td>0.068</td>
</tr>
</tbody>
</table>

effects of viscosity on the behavior of emanated jets are analyzed. In the former, the electrical charge is conducted on the jet surface through a high voltage power supply.

A 500 W halogen floodlight is used to illuminate the jet flows and a high-speed CCD color video camera (Casio EXF1) at a frame rate up to 1200 fps and with a resolution of about 900 dpi was utilized during imaging process. For each of nozzle geometries, two sets of images were taken by 0 and \( \pi/2 \) angles for elliptical, 0 and \( \pi/3 \) for triangular, and 0 and \( \pi/4 \) for square to observe the axis-switching phenomenon clearly. These camera views are schematically showed in Fig. 5. Furthermore, images were extracted from the recorded videos for subsequent analysis. In the end, we substitute the data to Image Pro Plus (IPP) software for detailed evaluation.

4. MEASUREMENTS AND UNCERTAINTY

Flow discharge for two mentioned experiment sets is gained with high accuracy via the direct method which is done by sampling Coleman and Steele (2009). Hence, the volume flow rate \( (q_v) \) and jet velocity \( (U_j) \) are defined as following,

\[
q_v = \frac{V}{t} \\
U_j = \frac{4q_v}{\pi D_h^2} = \frac{4V}{\pi D_h^2} = KV \, t^{-1} D_h^{-2} \tag{15}
\]

The measurement sensitivity of volume \( (V) \), time \( (t) \) and nozzles hydraulic diameter \( (D_h) \) are 0.4%, 0.5% and 1% in the given order. By considering Eq. (16), uncertainty for the jet velocity is in the acceptable value as 2.4%.

\[
\frac{\delta U_j}{U_j} = 2.4\% \tag{16}
\]

In analyzing the results, \( Re \) and \( We \) are two fundamental parameters that their uncertainties are writ-ten as below:

\[
We_j = \frac{\rho_j U_j^2 D_h}{\sigma} = \frac{\rho_j U_j^2 D_h}{\sigma} \tag{17}
\]

Here, errors of constitutive variables for these parameters are noted in Table 3. As it is seen, uncertainty for \( Re \) and \( We \) are 4% and 3.3%, respectively.

5. RESULTS AND DISCUSSIONS

The breakup length, penetration depth and wavelength of axis-switching beside frequency and sizes of the produced droplets and satellites are the main parameters investigated in this paper. As aforementioned, for studying nozzles geometry effects, video records and image processing are used. Fig. 6 illustrates breakup length for elliptical and triangular nozzles with distilled water.

For all studied non-circular liquid jets, a lower limit of \( We \) number prevents axis-switching. Fig. 7 presents images of liquid jets discharging in these conditions. This figure reveals that the axis-switching phenomenon does not show itself and jets degenerate to circular shape immediately after exiting from nozzles.

Dominance of surface tension forces compels the jet to take a circular cross section to minimize its surface energy and leads to the suppression of axis-switching process. With the glycerol addition, viscosity acts as a dampening agent and besides the surface tension forces overcome the inertial one. Therefore, the axis-switching starts to become visible at a threshold value of \( We \) which is denoted by \( We_{min} \) in this paper. As \( We \) passes the thresh-old value, the lateral inertia
of the liquid jet also increases and becomes comparable to surface tension forces and jet's viscosity. At this point, according to Tabatabaei-Hosseini et al. (2012), the free surface of the jet behaves like a stretched membrane which executes oscillations in the lateral direction and develops axis-switching.

The effect of liquid jet viscosity for this analysis is noticeable with emerging Ohnesorge number:

$$oh = \frac{\mu}{(\rho \sigma D)^{1/2}} = \frac{W_{e_{min}}^{1/2}}{Re}$$  \hspace{1cm} (18)

In quadrangular cross-section, $W_{e_{min}}$ has greater value than in triangular and elliptical ones. With Ohnesorge augmentation, the value of $W_{e_{min}}$ is also increased, which is a good indicator for the predominance of viscosity forces (see Fig. 8).

To better understand the obtained experimental results, they are divided into two distinct parts; the former part discusses the jet behaviour before breakup and the latter part includes the characteristics of jet properties after breakup.

### 5.1 Liquid jets properties before breakup

Non-circular jets have higher mixing rate due to larger entrainment where it comes from axis-switching effect. In the present study, the decay length of axis-switching $L_{as}$ demonstrates entrainment rate of non-circular jets. This length was defined as the distance measured from the nozzle exit to the point of axis-switching destabilization. The decay length depends on the intensity of surface tension and viscous forces, in charged jets and the second excited case respectively. It means, these opponent forces shorten the decay length in contrast to inertial force enhancing the axis-switching. The

The mentioned length is illustrated in the Fig. 9 for the case of distilled water. Fig. 9 shows the penetration depth for three nozzle types i.e., elliptical, triangular and quadrangular in different We values.

![Fig. 9. Axis-switching penetration depth for a) We= 59.15, b) We= 65.56 and c) We= 70.42.](image)

It can be concluded from Fig. 10 that increasing the applied voltage extends the decay length due to propagation of electrical charge on the jet surface and its repulsion forces. This fact is the major reason behind the variation of axis-switching wave-length. Moreover, it is clear that by adding the twin-vortex number, decay length decreases. We interpret that the elliptical nozzle with two twin-vortexes has a longer decay length comparing to the quadrangular one which has four. Also, for quadrangular jet, Las in Fig. 10 a and b are not observed due to its higher We

Figures 10 and 11 illustrate that the decay length increases with the Weber number augmentation in all studied nozzles for both excitation methods. It is noteworthy that in the second method of excitation, the decay length reduces with corners increment similar to charged jets. In the case of quadrangular jet, the axis-switching commences for higher Weber numbers, and this threshold value rises up with the viscosity augmentation. Accordingly, the decay length for quadrangular jet can be measured solely for distille water (Fig. 11a).

The mechanism of liquid jet breakup is influenced by a wide range of parameters, including the in-let condition before the jet’s emanation, the nozzle geometry, and the environmental situation into which the jet flows. Among all these affecting parameters, influence of the nozzle geometry has been overlooked in literatures despite the fact that nozzles with different shapes have already been considered for practical applications Reitz and Bracco (1982). The effect of nozzle geometry on the breakup length as well as its dependency on the number of corners are clarified throughout the current experiments. Here, the jet breakup length is defined as the distance measured from the nozzle exit to the point that jet breaks for the first time along its axis. Mean breakup length (Lb) was estimated from the individual measurements of jet breakup length obtained from photographs available for each flow condition. In the case of charged jets, attained values for this length do not have a distinctive trend.

![Fig. 10. Decay length variations as a function of applied electrical potential difference; a) We=48.419, b) We=51.573, c) We=55.275.](image)

The casual behavior of breakup length is due to the combination of axisymmetric and asymmetric waves on the jet surface. Because the electrostatic repulsive forces produced by free charges on the jet surface tend to trigger the asymmetric disturbances, earlier breakup happens Huebner and Chu (1971).

Variations of Lb/Dh for liquid jets exhausting from three types of nozzles are depicted in the Fig. 12 for the second method of excitation. It can be seen that the viscosity stabilizes the jet and tends to increase the breakup length. In fact, viscosity is a factor that prevails over the pinching effect caused by surface tension, and delays the breakup point Weber (1931).
Fig. 11. Axis-switching declination length function of Weber number for a) distilled water, b) GL1, c) GL2 and d) GL3.

Fig. 12. Variation of non-dimensional breakup length as a function of $W e^{0.5}$ in non-circular nozzles for utilized a) Distilled water, b) GL1, c) GL2 and d) GL3.
Fig. 12 reveals that in all used nozzles, unbroken length of the liquid jet increases with the flow rate augmentation. Also, it is clear from this figure that the breakup length of triangular nozzle is longer than elliptical nozzle for the whole range of We^{0.5}. This is due to twin-vortex number which is higher for triangular jet. Thus, increment of corner number is a factor in retarding the jet breakup. The recent result about the relationship between the breakup length and corners number stems from different surface energy level in each of nozzles. It is known that the surface energy of a circular liquid jet is lower than the surface energy of equivalent non-circular jets with axis-switching segments. Furthermore, ascending trend of surface energy carries out with the axis-switching segments propagation. On the other hand, a liquid jet or liquid ligament would disintegrate into spherical drops in order to reach a configuration with minimum surface energy. So, with increasing the number of axis-switching segments within the nozzle geometry, the surface energy of discharged liquid jet ascends and reaching the minimum surface energy takes much more time. The increasing trend of breakup length with the segments increment will face a problem in the case of quadrangular nozzle which will be more prominent by increasing the viscosity of jet, as can be seen in Fig. 12. The reason behind this abnormal behavior is the presence of transverse waves that appear on the jet surface after a critical value of We. Emerged waves destabilize the liquid jet. This phenomenon creates bigger segments which makes breakup length shorter. As a result, after a threshold value of We (We_{crit}) in quadrangular jet, transverse waves oppose liquid surface energy, and reduce its effect on increasing the breakup length. The growth of transverse waves on the quadrangular jets surface is shown in the Fig. 13 for two We numbers.

![Fig. 13. Transverse waves detected on quadrangular jet for two We numbers in the same time interval, A) We=79.304, B) We=90.684.](image)

As the viscosity augments, emerged transverse waves diminish. In this condition, dominant reason for disharmonic behavior of unbroken length of quadrangular jet comparing to the prior shapes is that the quadrangular jet behaves similar to the circular one. By increasing segments with greater curvature on the nozzle perimeter, its geometry approximate to circular form. Consequently, the quadrangular jet behaves like circular jet in upper viscosities. Also, a direct relation between the viscosity and this phenomenon is verified.

![Fig. 14. Axis-switching wavelength variations (λ_{as}/D_{eq}) as a function of applied electric potential difference; a) We=48.419, b) We=51.573, c) We=55.275.](image)

The wavelength of axis-switching (λ_{as}) is measured for all studied cases in both excitation means. By applying nozzles equivalent diameter (D_{eq}), which is obtained by Deq = (4A_0)/\pi, non-dimensional axis-switching wavelength is calculated Rajesh et al. (2016). Variations of λ_{as}/D_{eq} as a function of Weber number for all nozzle geometries are depicted in two distinct parts i.e., electrical and viscosity excitation methods.

Increase in variation of λ_{as}/D_{eq} with applied volt-age in the Fig. 14 was predictable, because the electrostatic repulsive forces caused by free charges on the jet surface tend to reduce the surface tension.
Since, the surface tension is a deterrent force against the axis-switching, increasing the amount of electrical charges on the jet surface prolongs the axis-switching and its wavelength. Also, we observe that the linear trend of $\lambda_{as}/D_{eq}$ with applied voltage holds true for all nozzle geometries. In all studied flow rates, the wavelength of axis-switching will decrease with the increment of twin-vortexes number. It means, elliptical nozzle with two twin-vortexes has a bigger wavelength in comparison to quadrangular one which has four.

The plots of $\lambda_{as}/D_{eq}$ for water and water-glycerol mixture jets show a linear variation which is consistent with the previous observations (Rayleigh 1879, Rajesh et al. 2016). Fig. 15 illustrates the linear trend of $\lambda_{as}/D_{eq}$ with We0.5 is accurate for all nozzles and the nozzle geometry does not seem to influence it. As aforementioned, the value of $W_{emin}$ for the case of quadrangular nozzle is upper than others, so measurements of $\lambda_{as}$ for quadrangular jet was limited to a narrow range of We numbers, and will be more narrow with the viscosity augmentation. Therefore, $\lambda_{as}/D_{eq}$ for this geometry covers a short range of We and is not suitable to illustrate properties after breakup.

**5.2 Characterization of Excited Liquid Jets**

Due to the effect of applied excitations and nozzle geometry on the produced droplets, the second part of experiments is assigned to the pinched droplets. These properties include droplet formation frequency beside droplet and satellite diameter variations for different nozzle geometries and working liquids. Owing to the ordinary breakup behavior of charged jets, it was not possible to get a definite behavior for the liquid jet properties after pinch-off. Therefore, this part represents the obtained results interpreted from the second excitation method.

Fig. 16 shows that droplet formation frequency raises with the velocity increment which can be explained by considering inertial forces. Further-more, propagation of glycerol amount in the solution (increasing the jet viscosity) enhances the viscous forces against the inertial ones and as a result, the formation frequency of droplet decreases.

Because of droplet size fluctuation, a minimum of 150 droplets for each solution of water-glycerol mixtures and flow rates were measured and the average size is reported in each situation. The diameter is recorded only when it had been separated from the jet completely and formed approximately a spherical shape. Fig. 17 depicts variation of non-dimensional droplet mean diameter for all utilized non-circular nozzles as a function of Weber number for different jet viscosity. This figure reveals, produced droplets from triangular jet are bigger compared to square and elliptical ones for the whole range of Weber numbers and different viscosities. Increment in corners or segments (twin-vortexes number) postpones the jet breakup while increases the mean diameter of detached droplets. The size of
Fig. 16. Variation of droplet formation frequency over We number for elliptical, triangular and quadrangular nozzles with a) GL1, b) GL2 and c) GL3.

Fig. 17. Non-dimensional droplet diameter as a function of We number; a) GL1, b) GL2, c) GL3.
disintegrated droplets is in a direct proportion with breakup length. Hence, the increasing trend of droplet diameter will face a problem in the case of quadrangular nozzle. The nozzle geometry which approaches the circular shape is the main reason for the mentioned inconsistency. It makes exhausted liquid jets to reach the minimum inter-face energy configuration sooner. Consequently, the breakup takes place sooner and droplets fail to grow completely.

From Fig. 18, effects of jet velocity and nozzle geometry on satellite formation are vivid. Two important points can be obtained from this figure; the former is the growth of satellites with increment of the flow rate, and the latter is the relation between satellite diameter and the number of corners (segments with greater curvature) on the nozzle perimeter. Both satellite and mean droplet have similar trends over We number for various nozzle geometries. Therefore, by corners augmentation, satellite size becomes bigger except for quadrangular nozzle.

6. CONCLUSION

Discharged liquid jet from three different non-circular nozzles with approximately same cross section areas has been studied experimentally. Two different methods which were based on the variation of liquid properties have been applied to excite exhausted jets. Identical experiments are conducted for all nozzle geometries in both excitation methods. The axis-switching process of non-circular liquid jets is investigated in the present study by measuring the jet axis-switching wave-length. Based on the present work, main conclusions could be drawn as below:

- For both propulsion methods, as We increases, the decay length of axis-switching L 으로 increases, however, increasing the number of twin-vortexes decreases this length. Also, charged jets with higher applied voltages have longer decay lengths.

- Breakup length, as an important parameter for jets, lacks a uniform trend for the first exciting mean. On the other hand, for viscose liquid jets, it is raised by augmentation of the We number.

- The unbroken length of viscose jets for nozzle with more twin-vortex number is higher except for quadrangular one, where transverse waves appear on its surface.

- The wavelength of axis-switching increases proportionally with the applied voltage and flow rate. Inversely, viscosity acts as a deterrent unit and reduces its wavelength. Moreover, for both excitations, elliptical jets has greater axis-switching wavelength in comparison to triangular and quadrangular jets.

- The increment of We number leads to produce more droplets and consequently higher formation frequency of droplets. In contrast, viscosity has a negative impact on droplet production frequency.

- The droplet and satellite diameters are in direct relation with We number. As We number goes up, the mean diameter of droplets and satellites
rise. Elliptical jets have bigger droplets and satellites comparing to quadrangular jets, while triangular jets possess the smallest ones.

REFERENCES


