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Liquid jet breakup for non-circular orifices under low pressures

Fujun Wang [a,b], Tiegang Fang [a,*]

[a] Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, USA
[b] School of Energy and Power Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China

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ABSTRACT

This study uses a high-speed visualization technique to investigate the breakup process and flow behavior of low pressure water jets issued from non-circular orifices including square, triangular, and rectangular shapes. These orifices have approximately the same sectional areas. Stability curve and Ohnesorge chart are employed to make a comparison with circular jets discharged from a circular orifice of the same sectional area. The analysis is carried out for gauge pressures varying from 0.1 psi to 70 psi with small pressure steps corresponding to a range from 0.7 kPa to 482.6 kPa in metric units. Axis-switching phenomenon is observed and analyzed through calculating the axis-switching wavelength and oscillation frequency for rectangular jets. It is found that results for circular jets agreed well with classic theory. Non-circular jets demonstrate enhanced instabilities as a whole compared to circular jets. The different behaviors of non-circular jets are reasonably explained by Rayleigh's oscillation theory. Axis-switching and aspect-ratio effect in rectangular jets is found to slow down the increase of breakup-length in the Rayleigh breakup regime. Square and triangular jets are more susceptible to wind effects and they are more unstable especially at higher pressure conditions. This can be concluded from the shorter breakup-length and narrower transitional region from the Rayleigh regime to the wind-induced regime as compared to the circular and rectangular jets. Axis-switching wavelength of the rectangular jets is found to increase linearly with increasing jet velocity and oscillation frequency decreases correspondingly.

Introduction

Liquid jet breakup and atomization has many practical applications, including process industries (spray drying, spray cooling), coating application (surface treatment, spray painting), combustion (burners, furnaces, internal combustion engines, jet engine, and rocket motors) and medical and printing applications (Lefebvre, 1989). Understanding the liquid breakup phenomenon is central to the spray systems with optimized design and improved performance. The breakup of a liquid jet emerging from a nozzle into a gaseous environment has been investigated for over 130 years. Extensive experimental and theoretical analyses have been made on the stability of a liquid jet to understand the mechanism of disintegration and to explore the factors that may have effects on the jet breakup process, such as surface tension, viscosity, aerodynamic forces, gravity, liquid turbulence, velocity profile, nozzle geometries, to name a few.

Investigations of circular jets

It seems that the first quantitative analysis of jet disintegration was conducted by Savart (1833). His study indicated that the breakup length is directly proportional to the product of the jet velocity and the jet diameter. Plateau (1873) performed the first theoretical analysis on the stability of a cylindrical liquid column and showed that the jet tends to breakup into drops, whose total surface area is less than that of the column, when its length exceeds its perimeter. Based on Plateau's theory, Rayleigh (1879) established a linear stability theory by ignoring the liquid viscosity and aerodynamic effects and assuming that the surface disturbance was infinitesimal. Considering only the capillary forces, Rayleigh concluded that the jet is unstable only when subjected to axisymmetric disturbance with a wavelength larger than the circumference of undisturbed jet. Rayleigh further defined exponential growth rate for this kind of disturbance and by referring to his work (1878), he found that the maximum disturbance does not correspond to the maximum wavelength necessarily but occurs when the wavelength reaches about half of the jet perimeter. Another theoretical analysis was conducted by Aslanov (1999), focusing on the surface tension effects. Based on the mass and

* Corresponding author.

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energy equations, he developed a theory for the breakup of a thin liquid jet issuing from an orifice, which agreed closely with Rayleigh's linear analysis. By using a kind of surfactant to reduce the dynamic surface tension, Lisong and Bain (2009) studied the surface tension effects on jet breakup experimentally. A similar method was employed by Skelland and Walker (1989) to investigate the surface tension effects on the jet breakup length, jet contraction, and drop size.

Rayleigh (1889) also investigated the stability of a viscous jet considering effects from both viscosity and surface tension. Weber (1931) further extended Rayleigh's work and proposed a theory for the low speed jet disintegration considering viscous effects and his analysis agreed well with Haenlein's experimental results (1932). Weber came to a conclusion that viscous effects are always to increase the wavelength of the disturbance at which the jet disintegration commences (1931). Ahmed et al. (2011, 2013) and Yan et al. (2004) employed Weber's theory as a basis and performed numerical calculation for some characteristics of the breakup process.

The disintegration of liquid jets in the above conditions belongs to the Rayleigh's breakup regime which is characterized by low jet velocities. With a higher exit velocity, the breakup gradually enters the first wind-induced, second-wind induced, and atomization regimes. In these regimes, aerodynamic effects become significant in the breakup process. As per Reitz and Bracco (1986), in the first wind-induced regime, aerodynamic forces amplify the small disturbances caused by surface tension and result in the disintegration of the jet into drops with a size comparable to the jet diameter. When reaching the second wind-induced regime, aerodynamic forces cause the jet to break up into much smaller drops near the nozzle exit. More investigations involving the aerodynamic effects on the liquid jet breakup were performed by Moses et al. (1999) and Gordillo and Perez-Saborid (2005).

Investigations of non-circular jets

Bidone (1829) made the first observation on the variation of the cross section of a jet emerging from a non-circular orifice. He noticed two different cases of liquid jet profiles. One is that a liquid jet emanating from the non-circular orifices can resolve itself into several very thin and broad sheets perpendicular to the jet direction and these sheets preserve its continuity until breakup occurs. However, when the orifice is relatively small and the injection pressure is low, expansion and contraction of these sheets take place periodically so that a recurrent surface is observed, which is referred as the axis-switching phenomenon later. This interesting phenomenon was later investigated more carefully by Magnus (1855) using several non-circular orifices including rectangular, triangular and square. Buff (1856) first gave a reasonable explanation to the axis-switching phenomenon by referring to the capillary force. A more descriptive explanation can be found in a recent work (2012) by comparing with a mass-spring system where oscillations are the result of the competition between surface tension and liquid inertia. Based upon these early observations (Bidone, 1829; Magnus, 1855), Rayleigh (1879) analyzed the axis-switching phenomenon. Rayleigh developed a relationship that the axis-switching wavelength is directly proportional to the velocity of the jet if a strict isochronism oscillation, where the oscillation amplitude is infinitesimally small, is satisfied. Nevertheless, Rayleigh pointed out that in most cases where the amplitude is considerable compared to the jet diameter, the wavelength variation may have a discrepancy due to the departure from the isochronism theory which results in a decreasing oscillation frequency with increasing jet velocity. Based upon Rayleigh's linear temporal analysis (1879), Bechtel (1989) obtained a nonlinear theory where the oscillation was not confined to small amplitudes by analyzing the motion of inviscid Newtonian fluid jets issued from elliptical orifices.

As reviewed by Birouk and Lekic (2009), some important factors that may influence the stability of the liquid jet such as aerodynamic effects, liquid turbulence, initial velocity profile, cavitation effects are not independent and they are actually related to the nozzle geometry design including aspect ratio, contraction ratio, contraction angle, orifice geometry and so on. Another review by McCarthy and Molloy (1974) also included the influence of the nozzle design on the stability of liquid jets. An attempt was made to get a qualitative relation between the nozzle shape and the issuing jet shape (the initial condition which determines the breakup process of the liquid jet). The importance of nozzle geometry has received researchers' attention. The review by Gutmark and Grinstein (1999) showed that noncircular jets could be used as an efficient technique of passive flow control to make the improvement of sprays in practical applications. McGuinness et al. (2005) investigated the influence of the nozzle design on the spray droplets and showed that smaller droplets can be generated by employing noncircular nozzles and further improvement can be achieved by using a three-dimensional nozzle.

More works dealing with the breakup of elliptical liquid jets were conducted by Kasyap et al. (2008, 2009) and Amini and Dolatabadi (2011, 2012). Kasyap et al. (2008) carried out experiments with water emanating from elliptical orifices with different orifice aspect ratios. By comparing the breakup curve of the elliptical jet with those of circular orifices with the same exit area, Kasyap et al. found that in a particular range of flow conditions, liquid jets emerging from elliptical orifices were less stable than jets form the circular orifice and he attributed this enhanced instability of elliptical jets to the axis-switching phenomenon occurring in the specific range. Kasyap et al. (2009) added water–glycerol mixture as a second working fluid in his later research. The axis-switching process was investigated more carefully through analyzing its wavelength and amplitude and the effects of orifice aspect ratio and liquid viscosity on the axis-switching process were revealed through this study. An analysis of the instability of elliptic liquid jets was performed by Amini and Dolatabadi (2011) by focusing on the Rayleigh breakup regime. They employed the one-dimensional Cosserat jet equations, derived by Caulk and Naghdi (1979), to get a solution to the asymmetric liquid flow. Results for circular and elliptic jets were compared and the elliptic jet was found to be more unstable. Furthermore, they showed that larger ellipticity increased the instability growth rate. Continuing their research in low speed liquid jets, Amini and Dolatabadi (2012) conducted experiments with low speed elliptic jets and focused on the spatial instability analysis to investigate the jet shape, axis-switching phenomenon, and breakup length. Another similar study was performed by Farvardin and Dolatabadi (2012) through numerical simulation to investigate the axis-switching phenomenon and breakup length of the elliptic jets with a volume of fluid (VOF) method. Numerical results were in good agreement with their previous experimental results (Amini and Dolatabadi, 2012).

Besides elliptic jets, there are also a very limited amount of works on rectangular jets. Konkachbaev et al. (2000) studied the axis-switching process of a rectangular liquid metal jet and their results showed a considerable deviation from the analytical correlations based on the 2-D inviscid theory. A more recent work concerning rectangular jets was done by Negeed et al. (2011) where the effects of orifice aspect ratio and the spray pressure on the breakup length and the size of formed droplets were studied.