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Interfacial oscillation of liquid jets discharging from non-circular orifices

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ABSTRACT

This work presents an experimental study on the oscillation behavior of liquid jets discharging from elliptical, triangular, and square shaped non-circular orifices. The measurements of wavelength and amplitude of jet oscillation are extracted from digital images of the liquid jets captured via still photography technique at different flow conditions using three different liquids (pure water, water-glycerol mixture, and Jet A-1 fuel). The measured wavelength of jet oscillation (λ), irrespective of the shape geometry of the tested non-circular orifices, increases linearly with increase in liquid jet velocity (U_o) and scales with the liquid jet Weber number (We) as $\lambda/D_{eq} \propto We^{0.5}$. The experimental measurements of λ recorded at different flow conditions exhibit good agreement with the theoretical predictions obtained using the mathematical model proposed by Rayleigh (1879) for liquid jet undulating in its cross section. For a given U_o, the liquid jet of Jet A-1 displays higher value of λ and undergoes a larger increase in λ along the axis of the jet compared to the jets of other two liquids. Further the trends on the variation of maximum and minimum amplitudes of the first wave segment of liquid jets discharging from the elliptical and square orifices with U_o are discussed.

1. Introduction

Understanding the flow behavior of liquid jets discharging from orifices is essential for several applications such as fuel spraying, ink-jet printing and aerosol devices in pharmaceutical industries. Although fundamental studies on the characteristics of liquid jets discharging from orifices are well reported in current literature, there is very little information available on the effect of non-circular shape of orifice on the fluid dynamic behavior of liquid jets. Seminal works on the influence of non-circular shape of orifice on the behavior of liquid jets are reported by Bidone (1829) and Rayleigh (1879). The details of jet shape transformations, developed due to the competition between liquid jet inertia and surface forces, in liquid jets discharging from large orifices of non-circular shapes such as elliptical and triangular are highlighted in Bidone's work. Theoretical description of these interfacial jet oscillations is given by Rayleigh (1879) by analyzing a cylinder of incompressible inviscid liquid with an undulating jet cross section of infinitesimal amplitudes. The influence of finite amplitudes in the undulating jet cross section in the theoretical description is incorporated later by Bohr (1909).

Systematic studies on the flow behavior of liquid jets discharging from non-circular orifices have been reported by several researchers particularly from elliptical orifices. Liquid jet with elliptical cross section at the orifice exit undergoes shape change as the jet moves along in the axial direction and shifts its elliptical cross section by right angle with respect to the initial cross section at a particular axial location. This periodic geometrical transformation superimposed with the axial motion of jet gives rise to the axis-switching phenomenon. Theoretical description of such oscillation of jet cross section is first proposed by Rayleigh (1879). The geometrical shape of non-circular orifice is one of the main parameters to govern the characteristics of these undulations. The number of undulations in the cross section of jet, n is taken as 2, 3, and 4 by Rayleigh (1879) for orifices of elliptical, triangular, and square cross sections respectively. The theoretical jet cross sectional shape is expressed by Rayleigh (1879) in polar coordinates as

$$r = a_o + a_n \cos n\theta \quad (1)$$

where r is the radial distance of jet, a_o, the mean radius of jet, and θ, the angular coordinate. Under the assumption that the amplitude of undulation, a_n is small compared to a_o, the temporal

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frequency of jet oscillation, p is estimated by Rayleigh (1879) as

$$p = \left(\frac{2}{D_{eq}}\right)^{\frac{3}{2}} \left(\frac{\sigma}{\rho_l}\right)^{\frac{1}{2}} \left(n^3 - n\right)^{\frac{1}{2}} \quad (2)$$

Here D_{eq} is the equivalent diameter of the non-circular orifice, σ, surface tension of jetting liquid, and ρ_l, the density of jetting liquid. If U_o is the velocity of liquid jet, then the wavelength of jet oscillation, λ is expressed as

$$\lambda = \frac{2\pi U_o}{p} \quad (3)$$

This flow phenomenon is often used to determine dynamic surface tension of liquids by measuring the wavelength of axis-switching segments of elliptical liquid jets. These investigations have helped to enhance the comprehensive understanding on the characteristics of axis-switching oscillations in elliptical liquid jets (Rayleigh, 1890; Bohr, 1909; Bechtel, 1989; Bechtel et al., 1995). For inviscid liquid jets issuing from elliptical, square and triangular orifices under the force of gravity, the profiles of interfacial jet oscillations are determined theoretically and the evolution of jet cross section is presented at different axial locations by Geer and Strikewada (1980, 1983) without and with surface tension effects. Further academic interest on the characteristics of elliptical liquid jets is shown in recent years mainly to understand the jet instability and breakup behavior at different operational conditions (Kasyap et al., 2008, 2009; Amini and Dolatabadi, 2011, 2012; Amini et al., 2014; Muthukumaran and Vaidyanathan, 2014; Sharma and Fang, 2014; Wang and Fang, 2015). For low Weber number conditions, the liquid jet discharging from an elliptical orifice is more unstable compared to the equivalent circular jet due to larger surface tension forces in the former. The enhanced instability with the increase in eccentricity of elliptical orifice on the jet breakup process is highlighted. The liquid jet discharging from higher eccentricity elliptical orifice breaks up faster.

The primary goal of this study is to describe the characteristics of interfacial oscillations of liquid jets discharging from elliptical, square and equilateral triangular orifices at different jet flow conditions. To date, except the seminal works by Bidone (1829) and Rayleigh (1879), to our best knowledge no others works are seen describing the interfacial jet oscillation characteristics of liquid jets discharging from such non-circular orifices at varying jet conditions. The details of jet oscillation characteristics could be useful to describe the instability and subsequent breakup behavior of these non-circular liquid jets. By considering the potential use of such non-circular orifices in practical applications of ink-jet printing (Bassous et al., 1977; Jeanmaire et al., 2001), fuel spraying (McHale et al., 1971; Baik et al., 2003; Sharma and Fang, 2015) and pesticide spraying (Dransfield, 1965), a systematic experimental study to investigate the characteristics of interfacial oscillations of liquid jets discharging from orifices of non-circular shapes such as elliptical, square and equilateral triangle with equivalent diameter approximately 4.82–4.97 mm is carried out. Experimental measurements on the wavelength of jet oscillation are obtained for three different liquid jets discharging from the abovementioned non-circular orifices at different flow conditions. The recorded experimental measurements are then compared with the theoretical predictions obtained using the mathematical model proposed by Rayleigh (1879). Further the role of liquid properties on the characteristics of wave segments of liquid jets discharging from the non-circular orifices at different flow conditions is described.

2. Experimental details

The experiments of liquid jet issuing from non-circular orifices are carried out in a standard test facility (Fig. 1) used in spraying studies. A large stainless steel tank is used to store the jetting

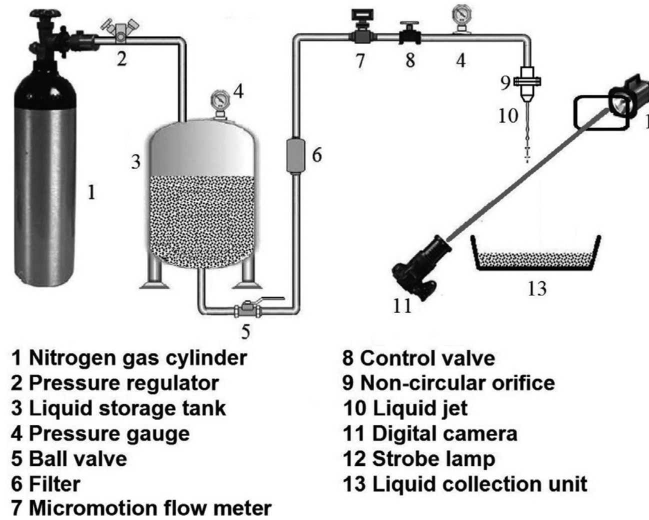

Fig. 1. A schematic of the experimental apparatus.

liquid under pressure by means of a compressed air supply and an air pressure regulator. A filter is employed between the tank and the orifice assembly to arrest contaminants in the flow line. The liquid flow rate, m from the orifice is varied using a flow control valve and a pressure gauge which is calibrated against a standard HEISE pressure gauge. For a given test condition, the pressure drop across the atomizer, ΔP and m are noted from the test facility. The non-circular orifices considered in the present study are of cross sectional shapes elliptical, equilateral triangle and square, identified here as *EL*, *TR* and *SQ* respectively. The orifices are made of stainless steel material and fabricated using electric-discharge machining (EDM) process. Fig. 2 shows images of the exit plane of the three non-circular orifices. The orifices are examined in the laboratory using a video microscope to extract their actual geometrical dimensions. Table 1 shows the salient geometric details of the three non-circular orifices. For the square and triangular orifices, the dimensions of sides are extracted from the respective high resolution images. The equivalent diameter of the orifice, D_{eq} is estimated from the orifice exit area, A_o as $D_{eq} = \sqrt{\frac{4A_o}{\pi}}$. It is evident from Table 1 that the area of cross section of the three non-circular orifices is almost same. During flow experiments, the test orifice is arranged at the exit of an orifice assembly unit ending with cylindrical tube of inner diameter 20.6 mm. The three different liquids, pure water, water–glycerol mixture (80:20 in the mass ratio) and Jet A-1 (aviation kerosene), referred here as *W*, *W-G* and *F* respectively, are used in the study. The physical properties for *W*, *W-G* and *F* are summarized in Table 2.

The experimental measurements of jet oscillation characteristics are obtained from the analysis of digital images of liquid jets captured through photographic techniques. A Nikon D7000 digital camera with diffused backlighting system is used to take photographs of liquid jets. The pixel resolution of the camera is 4928 × 3264. A zoom lens (AF Zoom Nikkor 80–200 mm *f*/2.8D) is employed with the camera to capture good quality pictures of jet characteristics. The diffused backlighting system is consisted of a strobe lamp with variable flash timing control (Sugawara Laboratories Inc., Japan) and a light diffuser arrangement. A good combination of the camera exposure time and the flash time of the strobe light is resulted in capturing high quality images of the jet. In order to extract more details of the features of jet oscillations, for each non-circular orifice, two sets of images are taken with a specific angular distance between the two camera views. The theoretical analysis on the jet oscillation structure of liquid