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Flow and breakup characteristics of elliptical liquid jets

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ABSTRACT

This paper presents the results of an experimental study on liquid jets discharging from elliptical orifices into still ambient air. The experiments were conducted with a set of elliptical orifices of approximately same area of cross section but varying orifice aspect ratio using water and water–glycerol mixture as experimental fluids. The flow behavior of liquid jets was analyzed using their photographs captured by an imaging system. The measurements obtained for the elliptical liquid jets were compared with the circular liquid jets discharging from a circular orifice of the same area of cross section. Elliptical geometry of the orifice results in a flow process by which the emanating liquid jet periodically switches its major and minor axes as it flows downstream of the orifice. In this paper, we attempt to characterize the axis-switching process through its wavelength and amplitude. For a given elliptical orifice, the axis-switching process is dominantly seen in a particular range of flow conditions. The effects of the orifice aspect ratio and liquid viscosity on the axis-switching process are revealed through this study. The experimental results on jet breakup show that axis-switching process has a destabilizing effect on elliptical liquid jets within a particular range of flow conditions and it results in shorter breakup lengths compared to the circular jet. The extent to which axis-switching destabilizes the jet is dictated by the viscosity of liquid. An increase in orifice aspect ratio destabilizes elliptical liquid jets with low viscosity like water; however, this behavior seems to get obscured in water–glycerol mixture elliptical jets due to high viscosity.

1. Introduction

Liquid jet breakup is a ubiquitous phenomenon in nature and is a classic problem in hydrodynamics. It is commonly observed in spray and droplet formation processes encountered with several practical applications. Academic interest in the problem of liquid jet breakup dated back to the 19th century. Seminal contributions on the flow behavior of liquid jets discharging from circular and noncircular orifices came from the works of Bidone (1829), Savart (1833), Magnus (1855), Plateau (1873), Boussinessq (1877), Rayleigh (1879, 1945) and Chandrasekhar (1961). Delightful accounts of the earlier works on liquid jet breakup can be obtained from the comprehensive review articles by Bogy (1979) and Lin and Reitz (1998). Lord Rayleigh (1945) carried out a linear stability analysis of an infinite cylindrical column of inviscid liquid and concluded that such a liquid jet is unstable to axisymmetric disturbances of wavelength exceeding the circumference of the unperturbed liquid jet. Weber (1931) included the effects of viscosity and ambient medium in the analysis of liquid jet breakup and found that the effect of viscosity is to change the wavelength of the most unstable disturbance. Haenlien (1932) conducted experiments on liquid jet breakup with different liquids and circular orifices and constructed jet breakup length versus jet velocity curve (breakup curve) from the experimental measurements. Jet breakup length is the length of the coherent portion of the jet measured from the orifice exit plane (Grant and Middleman, 1966; Lin and Reitz, 1998). Breakup length of the circular jet increases linearly with jet velocity in a range of low jet velocities, reaches a peak or critical point, and thereafter decreases with increasing jet velocity. As jet velocity increases, the ambient atmosphere starts influencing the liquid jet and asymmetric waves or transverse waves begin to grow on the jet surface. Weber's theoretical analysis by considering the effect of ambient medium revealed a peak in the breakup curve (Weber, 1931), however, model predictions of the jet velocity at the peak or critical point did not match with experimental results (Grant and Middleman, 1966). It was concluded by Phinney (1972, 1973) that, immediately after the peak, the ambient medium causes a sharp increase in the amplification rate of disturbances on the liquid jet which reverses the increasing trend of breakup length variation as observed with experiments (Grant and Middleman, 1966). Further increase in the jet velocity earmarks the presence of short wavelength disturbances on the jet surface over a range of jet velocities and the breakup curve shows a positive slope in this regime (Lefebvre, 1989; Blaisot and Adeline, 2000). Breakup

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length soon reaches a maximum with increasing jet velocity and the liquid jet operates in the fully developed spray regime or the atomization regime at very high jet velocities.

Despite all these advances, there exist some subtle areas in this jet breakup problem which have not received adequate attention in past. For instance, effects of orifice geometry on the behavior of liquid jets have never been consistently taken into consideration (Lin and Reitz, 1998). A liquid jet emanating from an elliptical orifice switches its major and minor axes by right angles in a periodic manner as it flows downstream (Bidone, 1829; Rayleigh, 1879; Taylor, 1960). Surface tension causes the elliptical jet cross section to oscillate about a circular figure of equilibrium like a stretched membrane and consequentially the elliptical liquid jet executes multiple axis-switching (Rayleigh, 1879). Schematic sketches of free surface boundaries of a liquid jet discharging from an elliptical orifice are given in Fig. 1. Fig. 1(a) and (b) shows the appearance of elliptical liquid jet in the major axis plane and the minor axis plane of the elliptical orifice, respectively. The sketches also illustrate axis-switching phenomenon observed with the elliptical liquid jet. Once the jet ejects out of an elliptical orifice, surface tension force tries to minimize the curved surface area of the jet by pulling the ends of major axis inwards and pushing the ends of minor axis outwards. Due to the lateral inertia of the jet, the movements of major and minor axes ends do not stop abruptly at the ideal circular cross section, i.e., the cross section with minimum surface area, but overshoot. This causes the outward moving minor axis ends to be pushed further outwards and the inward moving major axis ends to be pulled further inwards. This kind of geometrical transformation superimposed with the axial motion of jet gives rise to the axis-switching profile on the jet as illustrated in Fig. 1. The axis-switching wavelength, λ_{as}, is defined as the distance measured between two consecutive crests or troughs as shown in Fig. 1. Rayleigh (1890) developed a mathematical model to calculate the dynamic surface tension of liquids from the axis-switching wavelength of elliptical liquid jets. This model was further improved by Bohr (1909). Analytical and numerical studies have been reported on elliptical liquid jets with and without surface tension to understand the spatial evolution of the free surface (Green, 1977; Geer and Strikwerda, 1980, 1983). Bechtel et al. (1988a,b, 1989) studied viscoelastic liquid jets issuing from elliptical orifices and predicted the axis-switching behavior of the liquid jets theoretically for the special case of Newtonian jet with constant surface tension. Later their model was extended to devise a technique for the measurement of dynamic surface tension and elongational viscosity of liquids (Bechtel et al., 1995).

Except the above conclusions on the free surface evolution of elliptical liquid jets, the fluid dynamic behavior of such liquid jets is largely overlooked in the literature. For instance published works on the breakup phenomena of liquid jets issuing from elliptical orifices is very scarce in the literature despite the fact that these orifices have already been studied for potential practical applications (McHale et al., 1971; Snyder et al., 1989). Hoyt and Taylor (1978) reported from their experiments that they were not able to identify any regular breakup on elliptical water jets. In this paper, we present experimental results on the breakup of liquid jets issuing from elliptical orifices of different aspect ratios using water and water–glycerol mixture as working liquids. Additional experiments were conducted with a circular orifice of approximately same cross sectional area as that of the elliptical orifices for the sake of comparison purposes. This paper is organized as follows. The experimental apparatus and procedure used in the study are given in the next section which is followed by the presentation and discussion of the experimental results. In Section 3, we first describe the visual observations on elliptical jets at various flow conditions, followed by the characterization of the axis-switching process in detail. We then proceed to describe the breakup curves of elliptical and circular jets of both liquids and present evidences to establish the role of axis-switching in the breakup of elliptical liquid jets. Finally, the major results arrived from the experimental study are listed in Section 5.

2. Experimental details

A set of stainless steel orifices containing one circular orifice and five elliptical orifices of various aspect ratios were used for the study. The geometric details of the orifices are given in Table 1. Cross sectional areas of all of these orifices were approximately same. Elliptical orifices were manufactured by electro-discharge machining process. Note that, owing to the fabrication processes, there were differences in the cross sectional area between elliptical orifices and the circular orifice and the measured error in this regard was estimated to be less than 5%. Sufficient care was taken to minimize the errors in obtaining the contour for elliptical orifices. The maximum deviation between the actual orifice contour and the ideal elliptical contour (the contour obtained based on the major and minor axes dimensions of the elliptical orifice) was estimated to be less than 0.078 mm (3.1% of D_o of the circular orifice) for all elliptical orifices used in the present study. The surface roughness of internal walls of the orifices was characterized by cutting a sample orifice longitudinally and examining it with

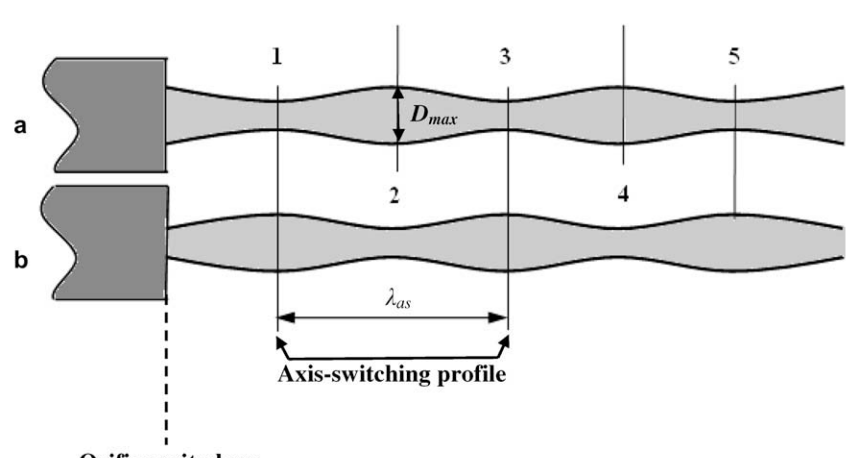

Fig. 1. Schematic sketches of an elliptical liquid jet discharging from an elliptical orifice. (a) Jet appearance in the major axis plane of the elliptical orifice, and (b) jet appearance in the minor axis plane of the elliptical orifice.