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Liquid Jet Breakup at Low Weber Number: A Survey

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Abstract

The instability and disintegration of liquid jets at low Weber numbers has important atomization applications specifically in drug delivery, electronic cooling and several others. Breakup of liquid jet stream from nozzle orifice leads to discontinuous flow which may be desirable or undesirable, depending upon the application. Jet breakup phenomenon have been divided into regimes that reflect differences in the appearance of jets as the operating conditions are changed. Four main breakup regimes have been identified that correspond to different combinations of liquid inertia, surface tension and aerodynamic forces acting on the jet, namely, the Rayleigh regime, the first wind-induced regime, the second wind-induced regime and the atomization regime. Plateau(1873) observed that the surface energy of a uniform circular cylindrical jet is not the minimum attainable for a given jet volume. He argued that that the jet tends to break into segments of equal length such that the spherical drops formed from these segments give the minimum surface energy. Rayleigh (1879a, b) showed that the jet breakup is a consequence of hydrodynamic instability & also considered the cases of a viscous jet in an inviscid gas (1892a) and an inviscid gas jet in an inviscid liquid (1892b). Weber modified Rayleigh's theory by considering the viscosity of the liquid and the aerodynamic force due to the ambient atmosphere. His analysis showed that the breakup length of the jet is inversely related to the jet velocity as there would be an increase in the growth rate of the prevailing disturbance. Most past studies have not been able to conclusively predict the breakup pattern in lower Weber number jets. Recently, an attempt has been made to resolve the breakup mode at low Weber number and to examine the influence of jet exit diameter on the breakup length. This survey traces the history of the investigation of the breakup of liquid jets and presents some of the latest work done in the field.

Keywords: Liquid jet, instability, break-up length, Weber number.

1. Introduction

The instability and disintegration of liquid jets at low Weber numbers is of importance in many atomization applications. These include drug delivery, coatings and electronic cooling, among others. Breakup of a liquid jet stream from nozzle orifice leads to interrupted or discontinuous flow which is desirable in certain applications and unsuitable for others. Therefore it is crucial to device a method to predict the break-up pattern of the liquid jet and factors on which it depends. Though, in practice, most applications could involve complex geometries and possibly liquids with varying rheological properties, a simple system under conditions that enable quantitative analysis would aid in providing a better understanding of the jet breakup process.

2. Literature Survey

The breakup of a liquid jet emanating into another fluid has been quantitatively studied for more than a century. [Plateau (1873)] observed that the surface energy of a uniform circular cylindrical jet is not the minimum attainable for a given jet volume. He argued that the jet tends to break into segments of equal length, each of which is $2\boldsymbol{\pi}$ times longer than the jet radius, such that the spherical drops formed from these segments give the minimum surface energy if a drop is formed from each segment.

[Rayleigh (1879a, b)] showed that the jet breakup is the consequence of hydrodynamic instability. Neglecting the ambient fluid, the viscosity of the jet liquid, and gravity, he demonstrated that a circular cylindrical liquid jet is unstable with respect to disturbances of wavelengths larger than the jet circumference. Among all unstable disturbances, the jet is most susceptible to disturbances with wavelengths 143.7% of its circumference.

Rayleigh also considered the cases of a viscous jet in an inviscid gas (1892a) and an inviscid gas jet in an inviscid liquid (1892b). He showed that if the mass of the gas is neglected, the most amplified disturbance in the first case possesses an infinitely long wave length and that for the second case it is 206.5% of the jet circumference.

[Tomotika (1935)] showed that an optimal ratio of viscosities of the jet and the ambient fluid exists for which a disturbance of finite wavelength attains the maximum growth rate. [Chandrasekhar (1961)] took into account the liquid viscosity and the liquid density, which was neglected by Rayleigh, and showed mathematically that the viscosity tends to reduce the breakup rate and increase the drop size. He also showed that the physical mechanism of the breakup of a viscous liquid jet in a vacuum is capillary pinching. The theoretical results of Rayleigh and Chandrasekhar appear to be in agreement with the experiments of [Donnelly and Glaberson (1966)] and [Goedde and Yuen (1970)].

[Weber (1931)] considered the effects of the liquid viscosity as well as the density of the ambient fluid. His theoretical prediction did not agree well with experimental data, as pointed out by [Sterling and Sleicher (1975)], who improved Weber's theory with partial success. Taylor (1962) showed that the density of the ambient gas has a profound effect on the form of the jet breakup. For a sufficiently large gas inertia force (which is proportional to the gas density) relative to the surface tension force per unit of interfacial area, the jet may generate at the liquid-gas interface droplets with diameters much smaller than its own diameter. This Taylor mode of jet breakup is the so-called "atomization" that leads to fine spray formation.

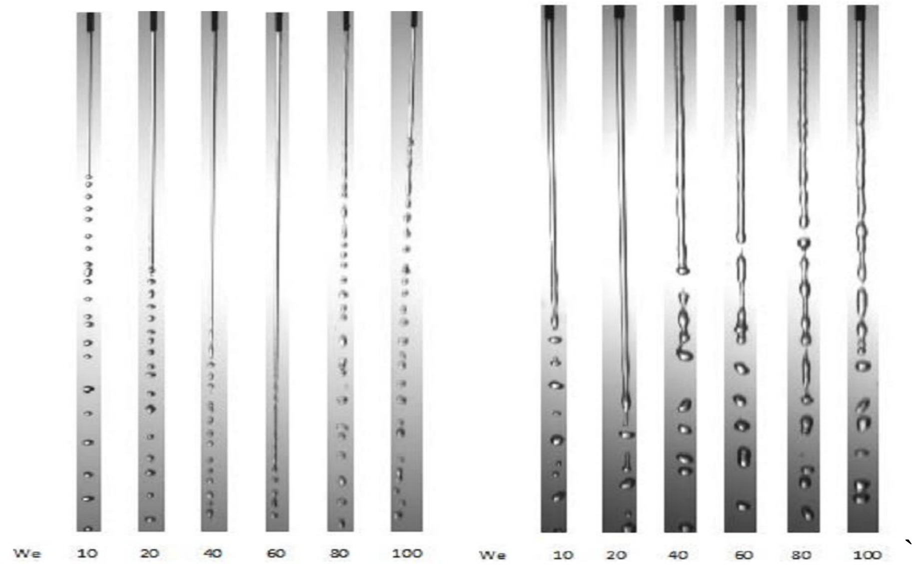
[Grant and Middleman (1966)] tested several liquids using a range of nozzles with diameters from 0.3 mm to 1.4 mm and L/d ratios ranging from 7 to 150. They used a high speed electronic flash unit (0.5µs) to capture shadowgraph images of the liquid jets. They found that Weber's prediction overestimated the critical velocity for low Ohnesorge number jets and underestimated it for high Ohnesorge number jets. They provide a correlation to predict the breakup in both laminar and turbulent jets. But they have observed that the predicted correlation was in poor agreement with the experimental results at sub-atmospheric conditions.

[Fenn and Middleman (1969)] established that the critical velocity observed in the breakup curve was a function of both viscous stresses and aerodynamic pressure forces. The critical gaseous Weber number of 5.3 that they obtained was found to be greater than Weber's prediction. For Weber number lower than the established critical gaseous Weber number, the breakup was observed to be independent of ambient pressure forces and depended only on the shear stress caused due to motion of the liquid jet. At larger Weber numbers, the effect of aerodynamic pressure forces became significant and increased the instability in the jet.

[Sterling and Sleicher (1975)] performed experiments with three different liquids and considered nozzles with small L/d ratio and those with large L/d ratios. Shadowgraph images taken at 24frames/s were used to capture the breakup process. With their experiment, they were able to establish that the results reported by [Fenn and Middleman (1969)] were due to velocity-profile relaxation effects and that aerodynamic forces affected the breakup. Their results too agreed that Weber's theory overestimated effect of aerodynamic forces and they provided modification to Weber's theory. Their modification was capable of predicting breakup for shorter nozzles but overestimated the breakup length for extended nozzles. [Kalaaji et al. (2003)] experimentally subjected the liquid jet to sinusoidal perturbations to obtain growth rate measurements in the Rayleigh and first wind-induced regime. They found that Sterling and Sleicher's prediction underestimated the rate of amplification of the disturbance as the spatial nature of the disturbance was not taken into account.

[Sallam *et al.* (1999)] found that the correlation suggested by Grant and Middleman for turbulent jets covered more than two modes of jet breakup as it was inclusive of the transition from laminar to turbulent and from turbulent to aerodynamic bag/shear breakup regimes. [Sallam *et al.* (2002)] identified three modes of liquid column breakup based on Weber and Reynolds number: weakly turbulent Rayleigh-like breakup, turbulent breakup, and aerodynamic bag/shear breakup. Water and ethanol were the jet fluids considered. They propose correlations to predict the breakup pattern in each of the three breakup modes. [Li *et al*.(2007)] tried to establish a relation between breakup length and the velocity for a circular impinging jet both experimentally and numerically by using two nozzle diameters.

[Rajendran *et al* (2012)]. noticed two distinct modes of breakup while observing the breakup phenomena for water jets at Weber number 10 to 110. For a given diameter, at lower Weber numbers, droplets get pinched off from the main jet stream. As Weber number is increased for the same nozzle diameter, a small ligament of jet liquid is seen to pinch-off from the main stream. These ligaments then, further breakup into droplets. These two distinct modes of breakup(non-ligamented mode and ligamented mode) are shown in Fig 1. As the diameter is increased, this ligament formation is seen to occur for progressively smaller Weber numbers. For diameter of 0.406 mm, ligamented mode of breakup is seen to occur around Weber number 80 and beyond. For Weber numbers below that, drops are seen to pinch off from the main jet stream. For a diameter of 1.499 mm, non-ligamented breakup mode is seen to occur until a Weber number of 30, beyond which ligaments are seen to be pinched off the main jet stream (Fig. 1(b)). For a diameter of 1.753 mm, ligament formation occurs at Weber number of 20 while for diameter of 0.279 mm, began at around Weber number of 80.



(a) Diameter = 0.406 mm **(b) Diameter = 1.499 mm**

Fig. 1: Breakup process in liquid jets showing ligamented and non-ligamented breakup [Rajendran *et al.* (2012)]

3. Conclusion

In order to predict the breakup length of a liquid jet in a jet stream, it is necessary to account for the forces acting in the process. Much of the previous work was focused on the identification of the modes based on Weber and Reynolds number which indirectly lead to the situation where we can predict the transition from the laminar to turbulent zone. However, recently the break up length has been found on depend on viscous and gravitational forces apart from inertial and capillary forces.

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