Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 51(6) (2020) 377-380
DOI: 10.22060/mej.2018.13828.5725

Experimental Comparison of Breakup and Flow Characteristics of Rectangular and Elliptical Water Jets

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ABSTRACT: The flow characteristics of water jets issuing from rectangular and elliptical injectors into quiescent air were experimentally investigated. Injectors were of the same cross-sectional area and a circular injector was also employed as the reference case. Digital images taken by a diffused backlight technique were processed to extract the main characteristics of the jet column at different jet velocities. The measurements were carried out for mass flow rates varying from 2 L/h to 120 L/h with small enough steps at low speeds to capture Rayleigh regime. Aside from the qualitative description of the jet flows, stability curve was plotted to make a comparison between different jets. The comparison revealed that the ellipse jet is the first one to reach the critical Weber number, while the circular jet remains laminar at higher velocities than the other two jets. Moreover, axis-switching phenomenon was carefully studied as the common characteristic of rectangular and elliptical jets. The wavelength and maximum amplitude of axis-switching were measured at different flow conditions and the results were compared. Though the axis-switching wavelength of both jets demonstrated a linear increment with Weber number, the rectangular jet was found to increase with a higher slope.

Review History:

Received: 13 Dec. 2017
Revised: 7 Feb. 2018
Accepted: 22 Apr. 2018
Available Online: 30 Apr. 2018

Keywords:

Liquid jet
Elliptical jet
Rectangular jet
Axis switching

1- Introduction

The history of investigation of liquid jets dates back to the 19th century when the need for breathing inhalers was strongly felt. After then, the study of jet breakup has made its way into many other fields of science and industry such as painting sprays, motion controllers of satellites, Internal Combustion (IC) engine injectors, ink injectors of printers, agricultural fountains and etc.

Ignoring the effect of ambient gas, liquid jet viscosity and the gravitational force, Rayleigh [1] presented the theory of temporal analysis. This theory suggests that a circular jet becomes unstable only if the wavelength of symmetrical disturbances exceeds the amount of perimeter of the jet. By considering the effect of liquid jet viscosity and gravitational force, Weber [2] developed Rayleigh's theory. Weber [2] arrived at this conclusion that the liquid jet viscosity increases the wavelength of disturbances at which jet breakup occurs.

The characteristics of a liquid jet discharging into a gaseous field and the growth of disturbances depend on several parameters. However, as indicated by Birouk and Lekic [3], the geometry of nozzle is one of the most effective parameters which has not been thoroughly investigated yet. Kasyap et al. [4, 5] experimentally investigated the behavior of jets emanating from six different elliptical nozzles of different aspect ratios.

Aside from elliptical jets, other types of non-circular nozzles have also been investigated. Sharma and Fang [6] carried out an experimental study to examine breakup behavior of high-pressure water jets issuing from different nozzles with circular, square, rectangular and triangular cross sectional area. Following this study, Wang and Fang [7] investigated axis-switching phenomenon and it was reported that axis-switching does not happen on water jets emanating from square and triangular nozzles.

With regard to the studies conducted so far, it is evident that fewer researches on rectangular jets have been performed compared to other types of nozzles. Negeed et al. [8] studied the liquid sheets breakup of a flat fan jet nozzle resulting from pressure-swirling. These few studies, revealed that rectangular jets share similar physics, particularly in terms of their interfacial oscillations with elliptical jets. The question then arises that how much a liquid jet issued from a rectangle differs from an elliptic one. To answer, in this study, we intend to investigate the main jet characteristics of a rectangular jet including breakup length and axis-switching characteristics, and to make a comparison with an elliptical jet of equal aspect ratio and exit cross section area.

2- Methodology(Experimental setup)

In this study, the flow characteristics of the liquid jet emanating from nozzles with circular, elliptical and rectangular cross sectional area were tested and compared. It should be noted that the cross sectional area and the aspect ratio of the both elliptical and rectangular nozzles were equal. Shadowgraph technique along with a high speed camera were employed for the purpose of flow visualization. Moreover, the flow rate of water was varied from 2 to 120 liters per hour that is correspondent to Weber numbers ranging from 0.5 to approximately 1100. A high pressure nitrogen capsule was used for pressurizing the liquid storage tank. The flow rate was controlled by 3 flowmeters

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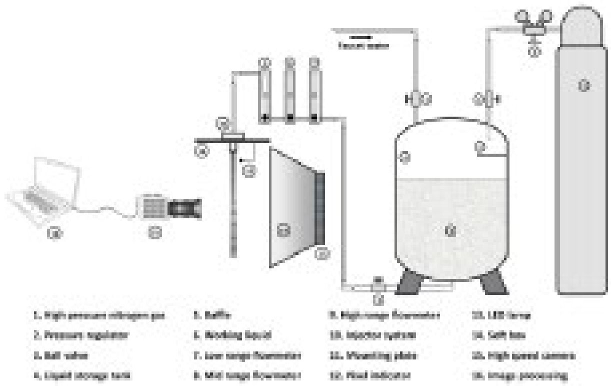

Fig. 1. Schematic of the experimental setup.

working at different flow ranges. Using shadowgraph technique for taking photos, an image processing code was developed to obtain required data from the photos. The experimental details of the current study are presented in Fig.1.

3- Results and Discussion

Shadowgraph technique creates the possibility of qualitative and quantitative analysis of the jet breakup which provides great assist in understanding of the physics behind the liquid jet. The shadowgraph images of the elliptical jet at different Weber numbers are given in Fig. 2. As seen in this figure, the elliptical jet exhibits similar behavior to the circular jet in Rayleigh breakup regime. Due to the dominancy of surface forces at low Weber numbers, the elliptical jet turns into circular form to have the lowest surface energy. The breakup length increases with the increment of Weber number until it hits its peak at Weber number of 1.85. After the critical Weber number, the effects of aerodynamic forces begin to appear over the jet and the first wind-induced regime is initiated. As a result, the breakup length experiences a downward trend because of the growing instabilities on the jet surface.

Axis-switching phenomenon is observed at first wind-induced regime for the first time. Weber number corresponding to the onset of axis-switching depends on the aspect ratio of exit area of the injector. By increment of Weber number, the instabilities grow on the jet surface and the symmetry which existed at lower Weber numbers begin to disappear. Due to the dominancy of inertial forces at higher Weber numbers, breakup length increases as well. The upward trend of the jet breakup from We=35.85 to the last measured Weber number is evident in Fig. 2. In this range, which is also known as second wind-induced breakup regime, the jet breakup is mainly due to the turbulence of the jet that induces high frequency instabilities with short wavelengths.

Inertia also affects the axis-switching phenomenon. To illustrate, at lower Weber numbers the number of axis-switching remained at six, whereas at higher We numbers it could even hardly reach two or three. Furthermore, as shown in Fig. 2, the wavelength of axis-switching decreases with the increase in Weber number. This is attributed to the fact that as the Weber number increases the effect of surface forces begins to disappear. Therefore, it takes longer for surface forces to alter the shape of jet cross-sectional area. For high Weber numbers, a set of chain connection in the proximity of breakup point, which has been marked by a red rectangle,

Fig. 2. Elliptical jet visualization for different Weber numbers

is observed on the jet surface. Also, lateral waves marked by yellow boxes, begin to emerge at higher velocities. It should be noted that, lateral waves root in the growing effect of aerodynamic forces and high level of turbulence of the flow.

Similar behaviour is seen for rectangular liquid jet.

The breakup length of the elliptical, rectangular and circular jets was obtained and the results are given in Fig. 3. It should be noted that the first disintegration point on the jet surface was regarded as the location of breakup. Overall, Fig. 3 suggests that all of the jets tested in this study display similar physical behavior which is in full agreement with the works in the literature [13, 14, 23]. With regard to Fig. 9, the jet breakup length increases linearly at low We numbers until it reaches the critical Weber number. After Wecrit the jet enters the first wind-induced breakup regime in which the aerodynamic effects amplify instabilities on the jet surface

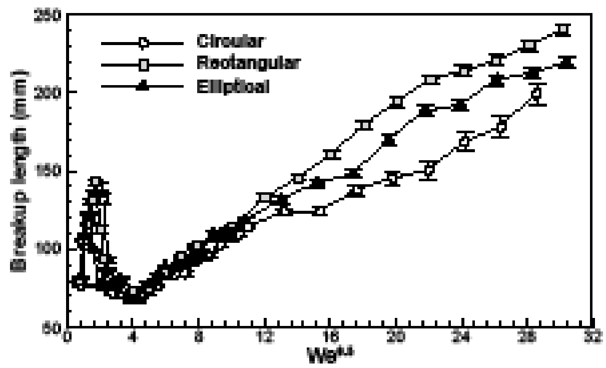

Fig. 3. Stability curve of all jets.

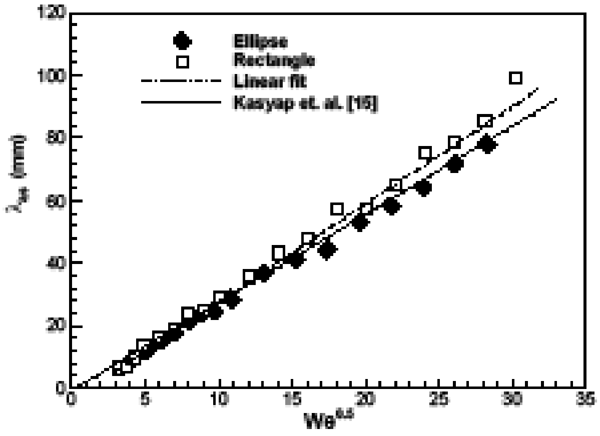

Fig. 4. Axis-switching wavelength versus We0.5

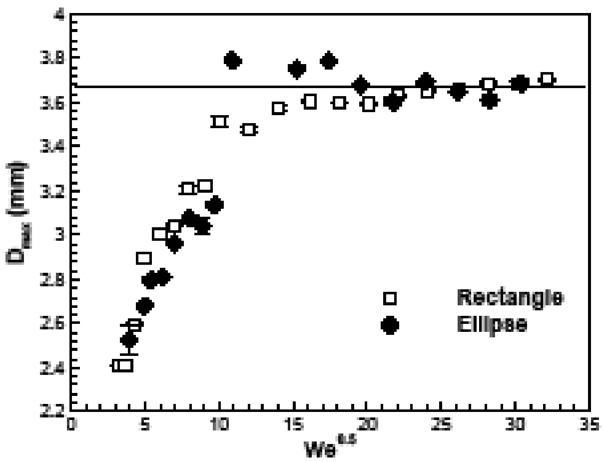

Fig. 5. Variation of axis-switching amplitude with We0.5

resulting in the sooner breakup of jet. Reaching its peak, the jet breakup length starts a downward trend falling to a Weber number after which the breakup length grows continuously. It should be noted that the minimum value of breakup length marks a point at which surface, aerodynamic and inertial forces are in an equilibrium status as the breakup length remains constant in the vicinity of this point.

The constant increment of the jet breakup length stems from the fact that after the absolute minimum value of jet breakup length, the effect of inertial forces outweighs that of the surface and aerodynamic forces.

The characteristics of axis-switching phenomenon which are wavelength and wave amplitude have been investigated for both of the rectangular and the elliptical jets. As the jet velocity increases the inertial forces strengthen and the surface forces diminish in importance. Consequently, liquid jet is able to move for a longer distance without breaking up and then axis-switching becomes visible.
The variation of the axis-switching wavelength with √We is illustrated in Fig. 4.

This figure demonstrates that the axis-switching wavelength grows linearly with the square root of Weber number which is in complete agreement with the works in the literature [15, 18, 21]. The comparison between the elliptical and the rectangular jets illustrates that at √We<12 the wavelength of the axis-switching phenomenon for both of the jets are almost equal. However, at higher Weber numbers the axis-switching wavelength of the rectangular jet is longer than that of the circular jet.

Variation of axis-switching amplitude with √We is also given in Fig. 5. Overall, both of the rectangular and the elliptical jets exhibit similar behavior in terms of the variation of the axis-switching wave amplitude. Unlike the rectangular jet whose amplitude rises constantly, the elliptical jet wave amplitude experiences a sudden increase.

4- Conclusion

The instabilities on the elliptical and the rectangular water jets with the same aspect ratios were studied. In addition, a circular jet was utilized as the reference shape for comparison. For the sake of flow visualization, shadowgraph technique was implemented and photos were taken by a high-speed camera. The experiments were conducted for different flow rates ranging from We=0.5 to We=1100. The structure and instabilities of liquid jets were studied in Rayleigh, first and second wind-induced regimes. The stability curve revealed that at lower velocities, the elliptical were less stable compared to the rectangular and the circular jets and enters the first wind-induced regime sooner. However, it was proven that at higher velocity the circular jet was the most unstable one. It was also shown that the axis-switching established by the rectangular jet owns a longer wavelength compared to the elliptical jet. Based on the obtained results, an empirical equation was also suggested for the axis-switching wavelength of rectangular and elliptical jets.

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