# Dynamics of liquid sheet breakup due to perforations in impingement atomization

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**Abstract**
In this work, atomization of the liquid sheet formed by two like-on-like impinging liquid jets is studied experimentally. The primary focus of the study is on sheet breakup due to formation and growth of perforations on the liquid sheet formed by impinging two liquid jets of 20 mPas viscosity. This perforation based atomization was not discussed adequately in the literature. In this mode of atomization, perforations or holes are originated at an area where the liquid sheet is thin due to stretching. As the time elapses, these perforations will grow in size and move either towards the bottom or towards the rim of the sheet, where they are converted into ligaments and these ligaments further break up into a chain of drops. To study the behaviour of perforation, the phenomena is captured using high-speed backlight imaging and processed using in-house developed image processing algorithms based on Matlab. For this purpose, from a series of images captured by the camera, perforations detected in a frame are tracked in subsequent frames until they get converted to ligaments. The kinematic and geometrical characteristics of perforations are obtained by tracking their centroid and area. It is observed that the perforations direction of movement depends on the position of its origin. Three modes of perforation based atomization are observed in this study. The growth rate of perforation and centroidal distance moved is observed to increase with jet Reynolds number.

**Keywords**
Impinging liquid jets, Atomization, Liquid sheet breakup, High-speed imaging, Image processing.

**Introduction**
When two liquid jets are made to impinge at a point, a radially expanding liquid sheet is formed in a direction perpendicular to the plane of the sheets. The formed sheet will be of circular in shape when the impinging jets are coaxial, otherwise a bay leaf like shaped sheet will be formed. Impinging jets are used when rapid mixing and atomization are required at the same time. Due to the applicability of impinging jet atomizers in bipropellant rocket engines and in many chemical processes, extensive research has been conducted on them. Heidmann et al. [1] conducted experimental analysis on impinging jets to study the atomization characteristics with respect to variation in geometric parameters of the impinging jets. They observed four different liquid sheet patterns which they named as closed rim, periodic drop pattern, open rim and fully developed pattern depending on the velocity. They defined the breakup length and observed its increment with velocity and viscosity of the liquid. Dombrowski and Hooper [2] conducted research on laminar and turbulent impinging water jets. They found that disintegration generally results from the formation of unstable waves of aerodynamic or hydrodynamic origin. Ibrahim and Przekwas [3] considered two breakup regimes of the sheet and developed models for predicting the shape and thickness. In one of the regime, the breakup is due to cardioidal waves which existed up to a Weber number of 500 while the other breakup regime is due to Kelvin – Helmholtz instability waves which occur above a Weber number of 2000. Anderson et al. [4] studied the spray characteristics of turbulent impinging jets. They measured the sheet breakup length, maximum spray width, and drop size as a function of flow velocity and injector geometry. They developed an analytical model based on linear stability theory to predict breakup length and drop size. Most of the impinging jet atomization studies in the literature were limited to atmospheric ambient conditions, very few studies focused on studies under elevated pressure and temperature conditions. Poulikakos [5] studied the nature of impinging jets at temperatures above atmospheric conditions ($25^0$C to $250^0$C) using water, ethanol and glycerol mixtures as working fluids. When the temperature is increased, the qualitative nature of the sheet remained the same but the quantitative characteristics changed. The size of the droplets resulting from the impingement of liquid jets started to decrease with increase in the temperature. Jung et al. [6] investigated breakup characteristics of liquid sheets as a function of jet velocity and ambient pressure. Experiments were conducted using water as working fluid varying jet velocity and ambient pressure up to 30 m/s and 4 MPa respectively. Dombrowski et al. [7] conducted photographic observations on modes of disintegration for various liquid sheets formed by different combinations of surface tension, viscosity and density with varying pressure with which the liquid sheet is formed. They discussed about two governing forces of liquid sheet stability, one inertial force and the second one being surface tension force. In their experimental

investigation, they observed perforations on the liquid sheet. Ahmed et al. [8] conducted an experimental study on liquid sheets formed by splash plate nozzle to observe breakup mechanisms with varying viscosity, flow velocity and nozzle diameter. For the range of parameters considered in their study, they observed two mechanisms namely Rayleigh-Plateau and Rayleigh-Taylor instability that governs the atomization process. They also correlated the transition from jet based break up to sheet based breakup by $Oh=75/Re^{1.1}$ i.e. at a given Reynolds number there will be a fixed Ohnesorge number for the transition to occur. Altieri et al. [9] conducted research on liquid sheets formed by spray nozzles using water and oil in water emulsions to identify the mechanism of sheet disintegration and the resulting drop size. They identified disintegration in case of water is by wave and rim breakup whereas perforation based disintegration is observed in case of oil in water emulsion. Neel et al. [10] conducted an experimental study on a liquid sheet formed by the impact of liquid jet on a solid surface to explore the reasons for the formation of perforation. They observed any external agent which tends to alter the surface tension of the liquid sheet initiate holes in the sheet. They presented some perturbation methods to alter the surface tension of sheet to initiate holes in the liquid sheet.

Extensive research has been done on mode of disintegration by wave growth and rim breakup. Few researchers have focused on the perforation based disintegration of a liquid sheet formed by splash nozzles. Even though similar kind of liquid sheet is formed by impinging two liquid jets, the mode of perforation based atomization needs to be investigated. Present study focuses on the atomization of liquid sheet formed by impingement of two like on like liquid jets by formation, growth and coalescence of perforations.

**Material and methods**

The experimental setup used for the present study is shown in Figure 1. The setup mainly consists of two injectors having 0.76 mm internal diameter set at 90º, a cylindrical pressure vessel to pressurize the liquid, a needle valve for precise control of flow, a high-speed camera in conjunction with a computer to capture the high-speed phenomena, tubing to ensure connectivity and a light source for backlight illumination. A 100 mm macro lens is used for the photography. Working fluid used in the study is obtained by proportionate mixing of glycerol and water to achieve 20 mPas viscosity, other properties of the working fluid include a density of 1190 kg/m$^3$ and a surface tension of 65.9 mN/m. Viscosity of the working fluid is measured using Brookfield Rheometer, surface tension is measured using Tensiometer and density using pycnometer. The working fluid is filled in the pressure vessel and is pressurized using compressed air from a compressor. Liquid at desired pressure is drawn from the pressure vessel via tubes and connectors to the injectors. A precise flow control is obtained with the help of needle valve placed before a digital pressure gauge. The pressurized liquid from the injectors impinge at a point and a radially expanding sheet is formed which is captured using a high-speed camera in conjunction with a light source and a computer. In order to observe the sheet formation and breakup phenomena, images are captured at a frame rate of 5,400 frames per second while the exposure is kept at 1/39000 s. Since the main aim is to study the growth behaviour of perforations; two algorithms are developed one for detecting the perforations and other for tracking the detected perforations.

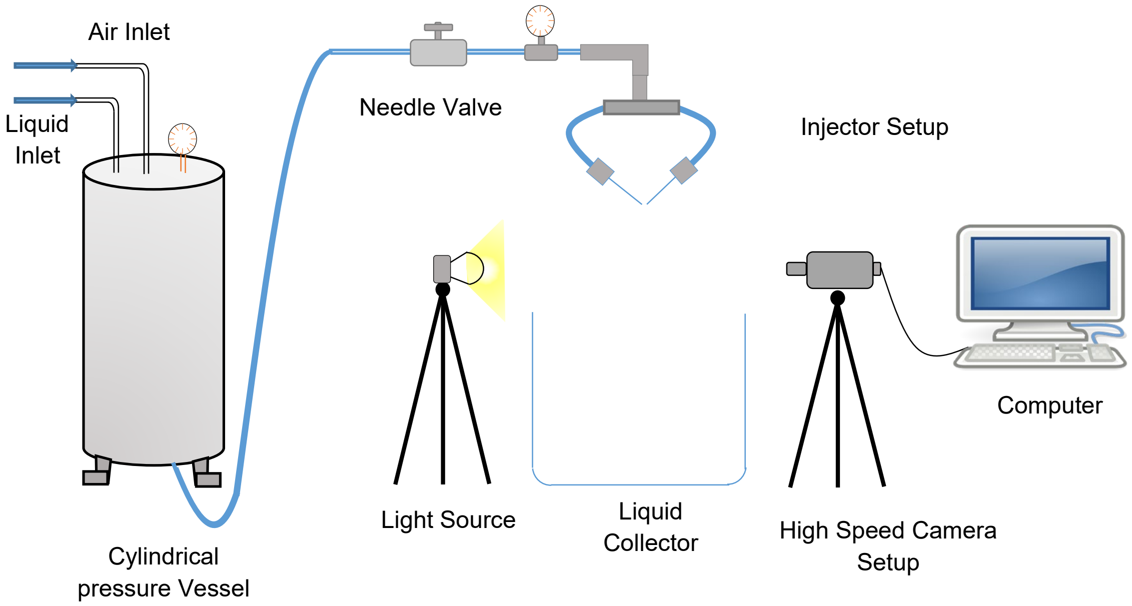


**Figure. 1.** Experimental Layout

The first algorithm (Figure 2) detects perforations in each frame and saves detected perforations region properties (Centroid, Area, Major Axis, Minor Axis, Perimeter, Eccentricity) into separate files. First, images are loaded into Matlab and the background image is being subtracted and pre-processing is done. Using a suitable threshold value, the edges were made darker. The threshold value is obtained by carefully observing the pixel intensity value of the perforation edges. Then Canny edge detection is applied to detect the edges of the perforations. Using 'regionprops' function of Matlab all the properties of connected components were obtained. Since a frame can contain many connected components to get connected components of perforations alone a mathematical comparison of all connected components in two consecutive frames is performed. Two consecutive frames were taken at a time and centroid distance change, area change, major axis change, minor axis change of all connected components are calculated. If the calculated changes are within the set limits (obtained by observing changes of region properties of perforations), then region properties of those connected components or labels were saved into files.

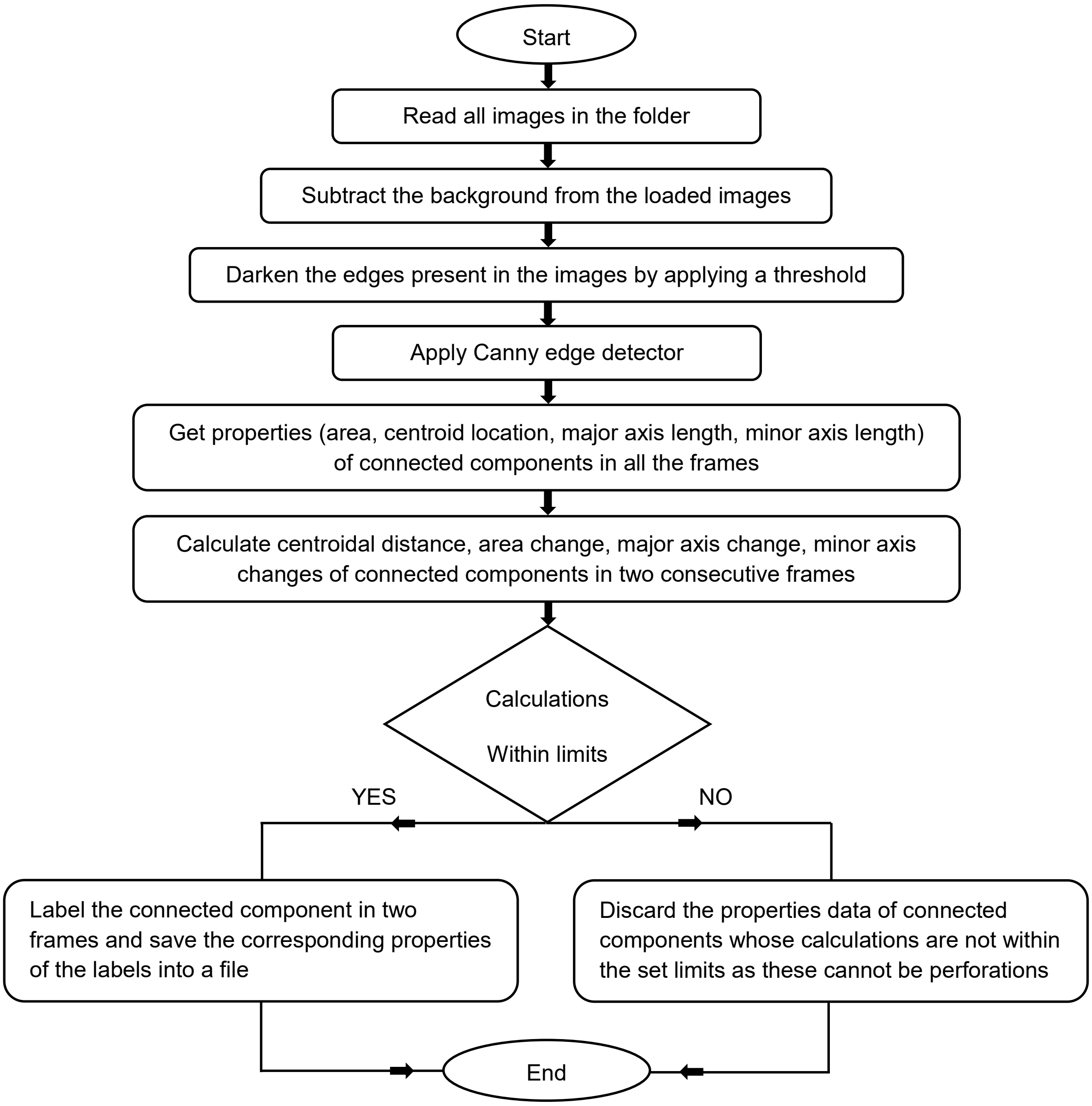


**Figure. 2.** Algorithm for detecting Perforations

The second algorithm described in Figure 3 keeps continuous track of perforations. The idea of tracking algorithm is adopted from work done by Naveen et al. [11] and modified according to the present study requirement. This algorithm deploys a Kalman filter for estimating the locations of perforations. The centroid data saved from the first algorithm is loaded into this algorithm. For the first frame, tracks are initialized directly from centroid data of the corresponding frame. From the next frame onwards Kalman filter starts estimating locations of perforations depending on the previous frame's tracking data. So now we have locations predicted by Kalman filter and locations from the detections file. Using these two sets of data a Hungarian assignment problem is formulated and solved. The assignment solver returns three sets of indices data namely matched tracks, unmatched tracks and unmatched detections. Matched tracks will be updated. Unmatched tracks will be deleted and new tracks will be assigned for unmatched detections. The same process is carried out for all the frames.

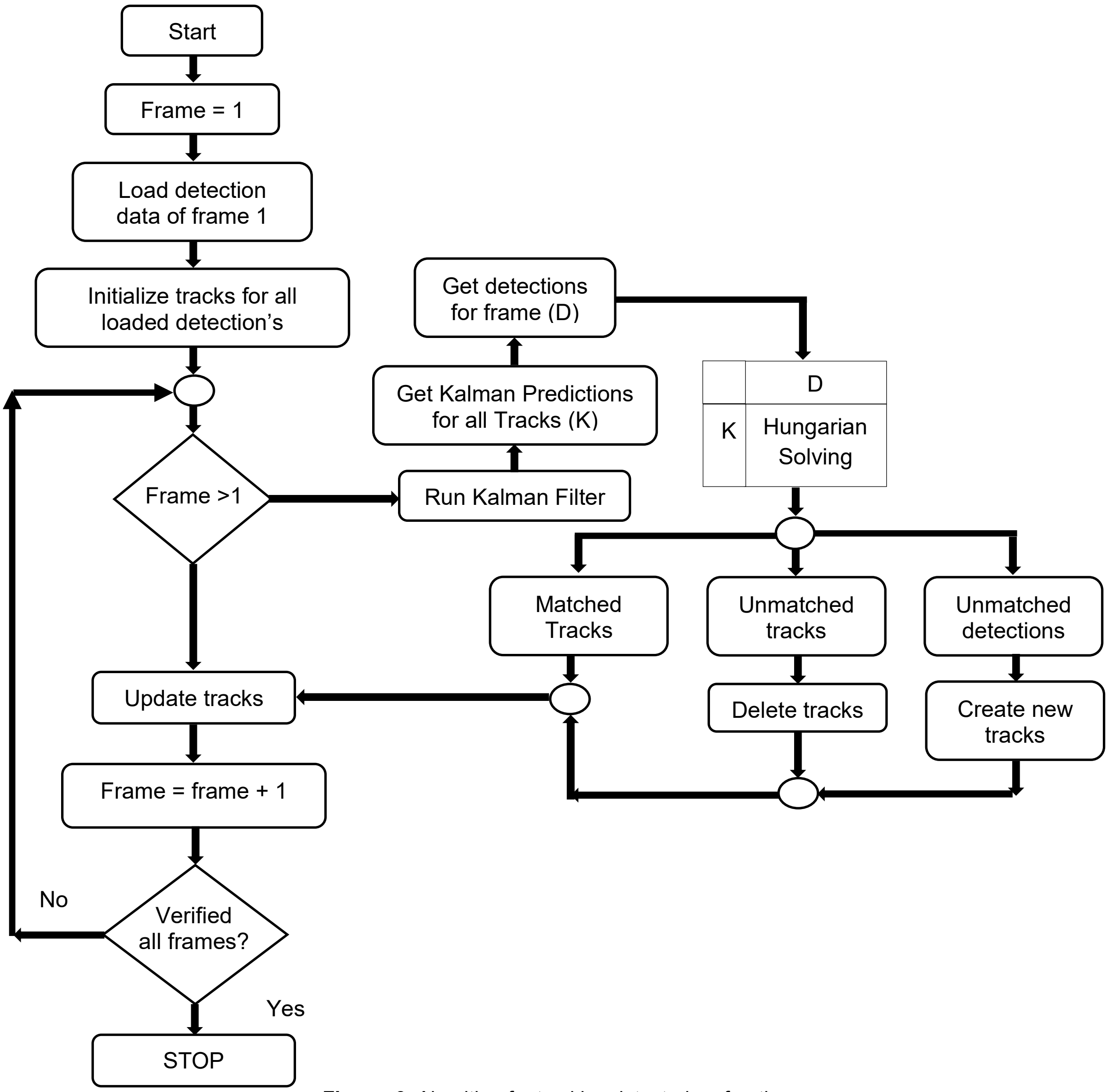


**Figure. 3.** Algorithm for tracking detected perforations

**Results and discussion**

The results of the present study include atomization of liquid sheet formed by impinging two liquid jets of 20 mPas viscosity. For the sake of completeness, the results are presented in two sections. Section 1 covers the atomization characteristics of liquid sheet as a function of Reynolds number. Section 2 covers the results of atomization of liquid sheet by formation and growth of perforations.

**Section 1:**

Figure 4 [a-j] shows development of liquid sheet with increase in Reynolds number. Figure 4 [a-c] shows liquid sheets whose disintegration is governed by capillary instabilities. In Figure 4a, a tiny liquid sheet is formed and drops being detached at the end due to capillary instability. Increasing the Reynolds number to 100 as in Figure 4b produces a liquid sheet with periodic drop shedding. At a Reynolds number of 150, the liquid sheet gets wider and any disturbances on the sheet are propagated along the sheet to the bottom merging point of the rim. This propagation of instabilities is clearly visible on the rim of the sheet. Perforation based atomization is first evident at a Reynolds number of 200 as shown in Figure 4d. As Reynolds number is increased further the density of perforations increases. Impact waves are evident for Reynolds number above 250 as shown in Figure 4e. As the Reynolds number increases the sheet becomes wide, this is due to the increase in velocity. As velocity of the jets is increased the momentum force is greater than the surface tension force. This results in a wider sheet. Also as the sheet is widened it also becomes thin, hence more number of perforations are formed. Figure 4i and j shows liquid sheets with a large number of perforations along with impact waves. As the velocity is increased the intensity of impact waves is also increased. This can be attributed to the increased air resistance on the liquid sheet as a result of increase in velocity.

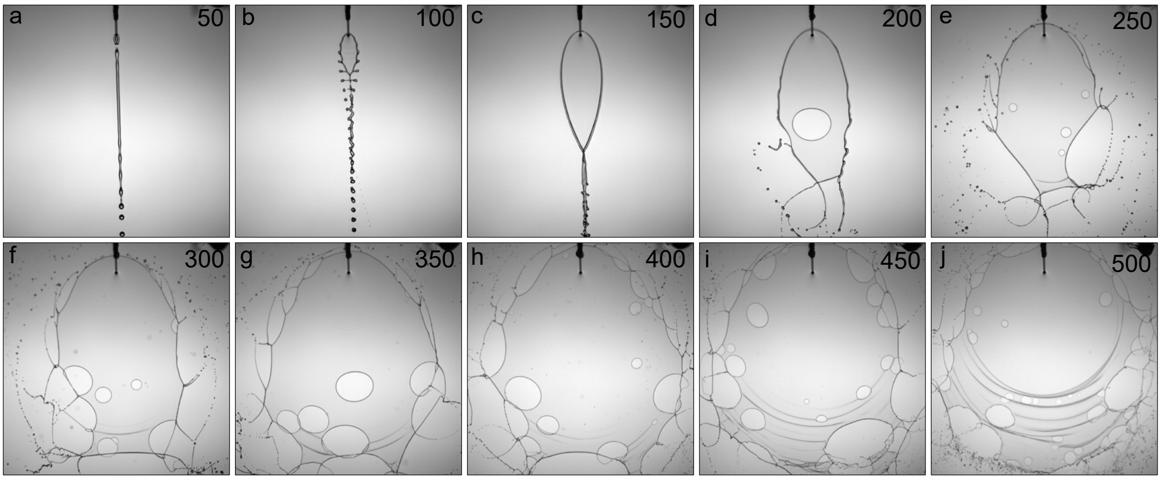


**Figure. 4.** Development of a liquid sheet with increase in Reynolds number

**Section 2: Perforation based atomization**

Atomization of liquid sheet by formation and growth of perforations is discussed in this section. These perforations are generated at an area where the liquid sheet is thin due to stretching. Generally, any perforation formed on the sheet grows in size with time due to stretching of the sheet until they are converted into ligaments. These ligaments are broken down to chain of drops due to interaction with surrounding air. The growth and behaviour of perforations depend on its area of origin. There are many ways by which these perforations ultimately get converted to drops which are described in this section as different cases.

**Case 1: Single perforation on liquid sheet:**

Usually, only one perforation is formed on the liquid sheet at low velocities where liquid sheet formed due to impingement of two liquid jets will have a stable rim. The single perforation formed on the sheet grows in size with time and reaches either bottom or rim of the sheet to disintegrate into ligaments and these ligaments further into a chain of drops. Figure 5 shows a typical case of single perforation formed on liquid sheet obtained by impinging two 20 mPas liquid jets. In this case, the perforation is formed close to the centre of the liquid sheet, hence the movement of the perforation is downward straight with size increment. Evolution of single perforation with time is shown in Figure 5 [a-l]. The numeral '1' at the centre of perforation in all the images indicates that the perforation is detected and tracked across the frames. Figure 5a shows the frame where the perforation is detected for the first time, so time is considered as 0 µs and the subsequent images from Figure 5 [b-l] shows its growth with respect to time. The actual time interval between two consecutive frames captured by the high-speed camera is 185 µs but only alternate frames are presented in Figure 5 [b-l] where the time interval between any two frames is 370 µs. As seen from Figure 5[b-l] the perforation grows smoothly in all directions till 2590 µs after which its growth is hindered by the surrounding rim. This perforation after interacting with the rim forms thin ligaments, where these ligaments further break down into droplets.

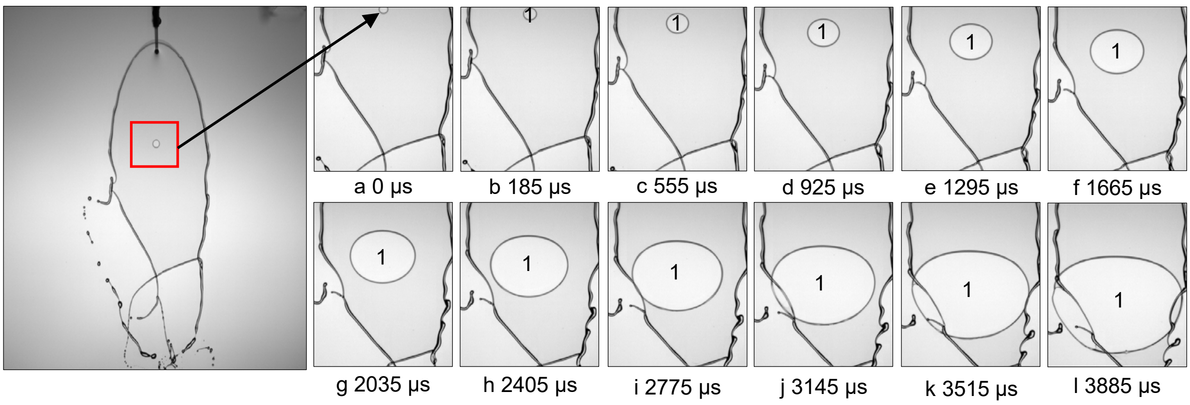


**Figure. 5.** Evolution of single perforation on liquid sheet

Figure 6 shows evolution of perforation in terms of equivalent diameter with time for the tracked perforation until 4070 µs. The slope of the curve indicates rate of growth of the perforation. It can be observed that there is an abrupt change in slope (or growth rate) of the curve from 2590 to 2775 µs which is due to the impact of perforation with the rim. From the time of origin of the perforation (0 µs) to 2590 µs the growth rate of perforation increases from 4.92 to 6.36 m/s, but for 2590 to 2775 µs the growth rate changes from 6.36 to 1.64 m/s. This sudden change is due to the obstruction being offered by the rim of the sheet for the perforation expansion. The two corresponding frames are showed inside the plot, where at 2590 μs the perforation is near to the rim and at 2775 μs the perforation has interacted with the rim. Again from 2775 to 2960 μs the growth rate increases and beyond 2960 μs the growth rate keeps on decreasing till 4070 μs where the rim of perforation starts disintegrating into ligaments and drops.

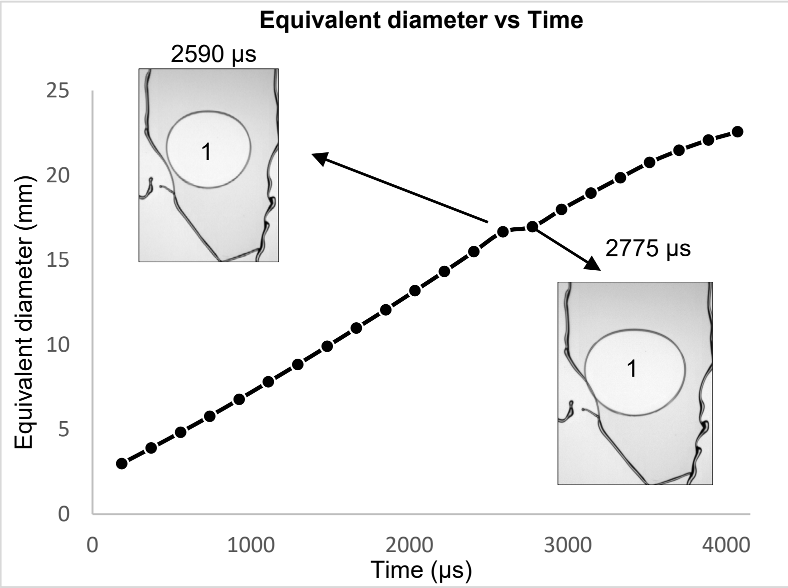


**Figure. 6.** Change of equivalent diameter with time for a single perforation formed on a liquid sheet

**Case 2: Coalescence of perforations**

When the velocity is increased from single perforation case, formation of multiple perforations is observed on the liquid sheet. Due to increased number of perforations, probability of interaction between them with in the sheet also increases. Interaction of these perforations on the liquid sheet has resulted in different kind of structure depending on relative size and location of the perforations.

**Coalescence of two perforations of approximately equal size originated close to each other**

Generally, when two perforations of equal size are originated at the same time or having approximately same area are collided, their common contact area is converted into a thin ligament which further breaks up into small droplets. Eventually, these two perforations merge into a single perforation and grow in size with time. This merged perforation depending on its position further reaches rim or centre to form ligaments and drops. Figure 7 [1-14] shows a typical case where two equal sized perforations originated close to each other collide and merge into a single perforation. The time interval between two images is 180 μs. The diameter of the perforations is around 0.8357 mm at the time of collision.

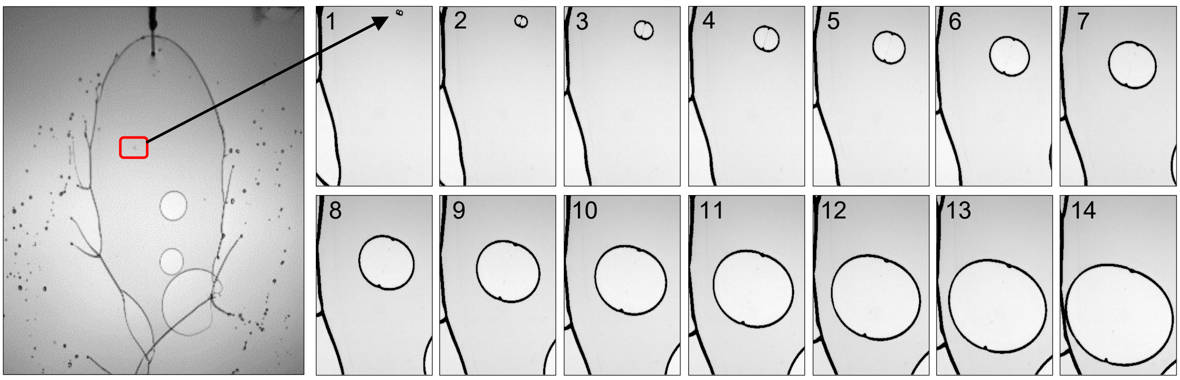


**Figure. 7.** Merging of two equal sized perforations originated very close to each other at a Reynolds number of 250

Figure 8 shows an another case of perforation interaction where two perforations of approximately equal size originated very close to each other. Here two equal size perforations originated near the rim grows towards each other with time and merge into a single perforation. Before merging the liquid bridge between them is converted to a ligament which disintegrates into droplets in the later stage. Finally, the two perforations merge into a single perforation. Figure 8 [1-2] shows liquid bridge being transformed into a ligament and figure 8 [3-10] shows the stretching of the ligament which results in a single perforation. Figure 8 [11-12] shows the growth as a single perforation with respect to time. Similar to the case 1 shown in figure 7, the time interval between two frames is 180 μs.

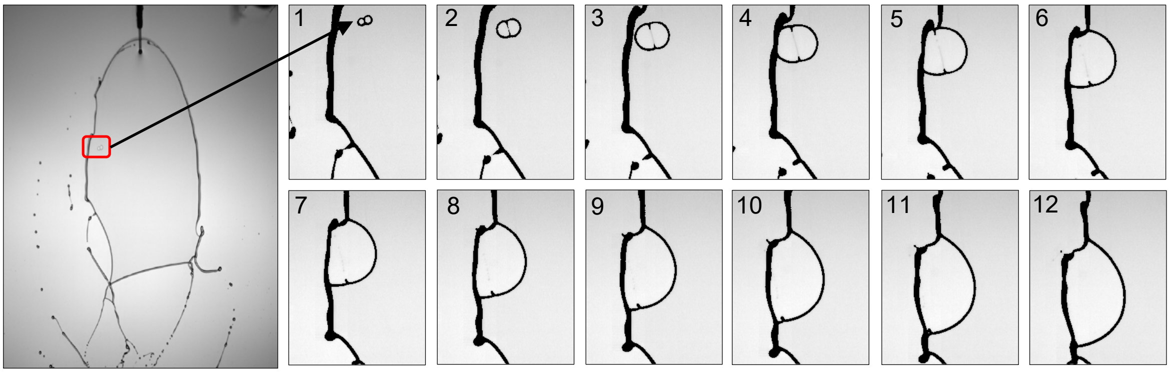


**Figure. 8.** Merging of two equal sized perforations originated very close to each other at a Reynolds number of 225

**Coalescence of two or more perforations having different size**

When two perforations of different size originated at different locations on the sheet are interacted, their rims cross each other and form a liquid sheet with a distinct rim. Due to differences in movement of the two rims, liquid sheet formed undergoes twisting action and forms a chain of tiny liquid sheets. Continued twisting as well as interaction with surrounding air leads to break of the liquid structures into droplets. Figure 9 [1-14] shows one such typical case of twisting. The time interval between two frames is 180 μs. Here the expanding perforations are being surrounded by the rim. In frame 2 the two perforations have just interacted. The rims of the two perforations crossed into each other trapping the liquid contained between them prior to collision as seen in frame 3. As the two perforations expand the boundary formed by their rims undergo twisting as seen in frame 4 and 5. As the expansion increases the intensity of twisting also increases as seen in frames 6 and 7. Since these twisted ligaments are also being stretched they start disintegrating into a chain of drops as seen from frame 8 onwards till frame 14. In few cases, it is observed that more than two perforations are interacted to disintegrate into drops with intermediate mechanisms similar to the case of two perforations. Such cases are primarily observed at high velocity of the jets due to wider and thin sheet. In some cases, impact waves interact with perforations where the rim of perforation which is in contact with the waves is detached from the perforation as a ligament and it gets converted into drops.

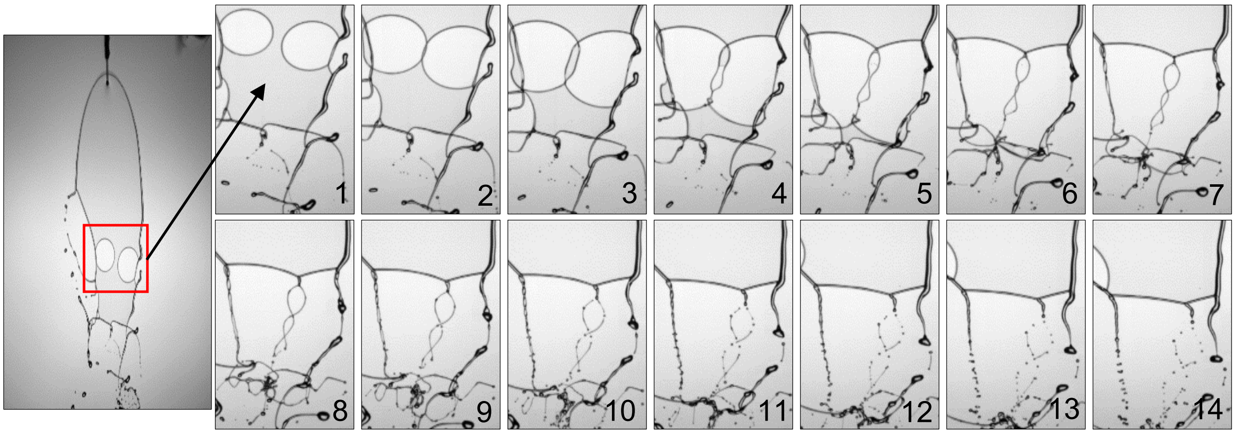


**Figure. 9.** Interaction of two perforations leading to twisting of common area.

Sequence of images with single perforation at different Reynolds number are processed to obtain time evolution in terms of equivalent diameter and movement of perforation as shown in Figure 10. Figure 10a shows variation of equivalent diameter for a single chosen perforation against time at different Reynolds number for the liquid sheet formed by 20 mPas liquid jets. From each Reynolds number case some frames are selected where a single perforation growth is tracked and corresponding area and centroid location is obtained. It is observed that as Reynolds number is increased growth rate of perforation increases. This is because at higher Reynolds number the radial velocity of liquid is higher and hence the rate of perforation growth is also higher. Also for a considered Reynolds number the growth rate of perforation increases until the perforation is met with rim or any other perforation. Figure 10b shows centroidal distance moved by a single perforation against time for various Reynolds number. Here also as the Reynolds number is increased the perforations moves at a faster rate. For a considered Reynolds number, the rate of centroidal distance moved is observed to be almost constant and it increased from an average of 5.67 m/s at a Reynolds number of 200 to an average of 12.82 m/s at a Reynolds number of 450.

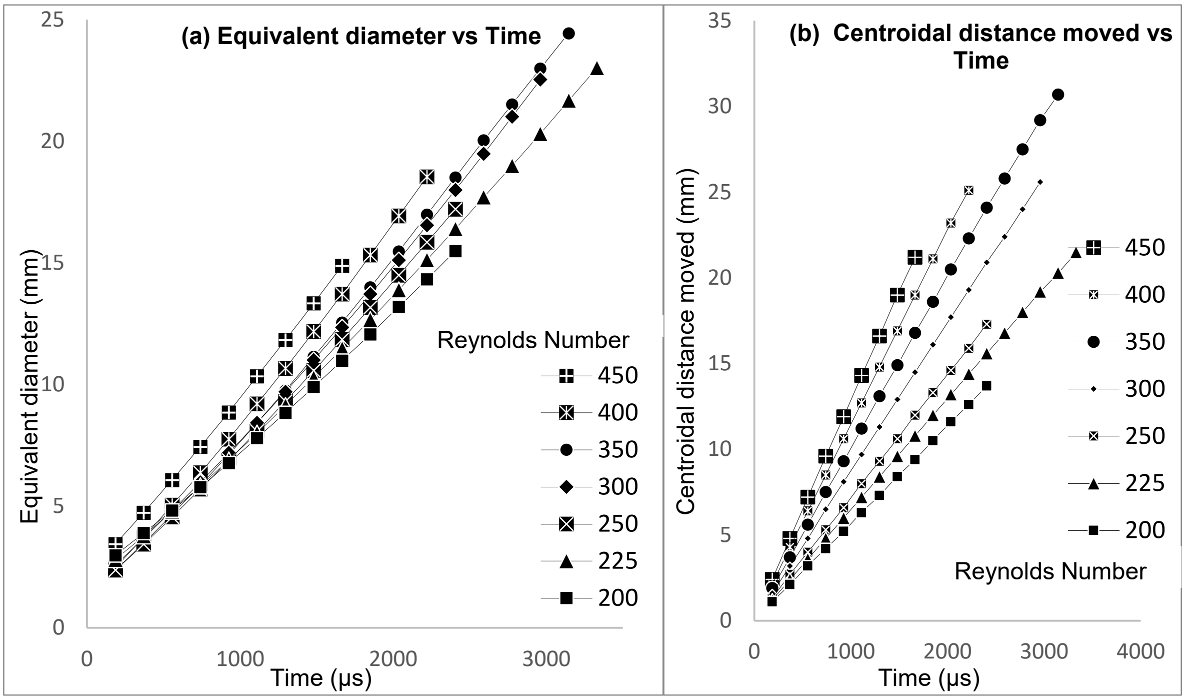


**Figure. 10.** (a) Change of equivalent diameter with time for single perforation with increasing Jet Reynolds number

(b) Centroidal distance moved with respect to time for single perforation with increasing Jet Reynolds number.

**Conclusions**

Experimental observations are made to study the atomization characteristics by formation and growth of perforations on a liquid sheet formed by impinging two liquid jets of 20 mPas viscosity. Formation and growth of perforation depend on the liquid jet Reynolds number. Hence, liquid sheet breakup characteristics at different Reynolds numbers is studied by changing liquid jet velocities. It is observed that for a Reynolds number below 200 there is almost no sign of perforations on the liquid sheet. In this case, disintegration is governed by capillary instability. Formation of perforations is evident above a Reynolds number of 200, this is because liquid sheet must be thin enough to initiate perforation formation. So as the Reynolds number increases the number of perforations formed on the liquid sheet increases due to the fact that the sheet becomes thinner. It is observed that perforation based atomization generally takes place by three modes. First mode is interaction of perforation with the rim, second one being coalescence of two or more perforations and the last mode is interaction of perforation with impact waves. In all the modes the perforation rim is converted into ligaments which further break into drops. The rate of growth of perforations and centroidal distance moved is found to increase with increase in Reynolds number.

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