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Studies of Jet A1 Fuel Atomisation Through Non-Circular Orifices

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ABSTRACT

The performance of the liquid rocket engine depends on the atomization behavior of the fluid being injected into the combustion chamber. Generally, a plain injector with a circular orifice has been used in the injector, but it has the disadvantage of having a low spray cone angle. The breakup length, mean droplet diameter, and Sauter mean diameter is also higher. Thus, to overcome these drawbacks, non-circular orifices have been utilized in the present study. The shapes used for non-circular orifices are semi-circular and plus. The results obtained with the non-circular orifice is compared with the circular orifices of the same area ratio. The working fluid used for the studies is Jet A1 fuel. Studies were also conducted with different L/D ratios by choosing an effective orifice length to reduce the upstream losses. The axis-switching phenomena were observed with the semi-circular as well as with the plus jets. The mean droplet size of the circular jets was more prominent compared to non-circular jets, and the Sauter mean diameter of non-circular jets droplets was smaller than that of the circular jet droplet. The spray cone angle has increased by 290% for plus jets and 30% for semi-circular jets compared to circular jets.

Keywords: Jet A1 fuel; Spray; Atomisation; Non-circular orifice; Sauter mean diameter

1. INTRODUCTION

Jet fuel is becoming highly attractive for rocket and gas turbine engines[1-2]. The common jet fuels are Jet A, Jet A1, JP-5, and JP-8. Using these fuels in rocket engines requires proper atomization as the combustion efficiency is highly dependent on it[3-7]. To achieve this, various types of injectors have been developed and are being used in the liquid rocket application. It includes a showerhead, doublet, triplet, ring slot, coaxial, splash plate, etc.[8-9]. Generally, plain atomizers are used for these types of injectors. It is mainly due to its simplicity in manufacturing, cheap and ruggedness. But it has the disadvantages of having relatively larger droplet diameters, larger breakup length and a smaller spray cone angle in comparison to other atomizers. The atomization efficiency is very less and it leads to the reduced combustion efficiency of the system. Attempts have been made by the researchers to address these issues by varying the injector orifices shape from circular to non-circular orifices in addition with an appropriate L/D (length to diameter) ratio[10-16].

A non-circular orifice possesses the three-dimensionality flow behavior, which makes the jet far unstable when compared to circular orifice[17]. These non-circular jets have been addressed to be an efficient passive flow control technique, which improves the performance of various practical systems only with a change in the geometry of the injector[10-12]. The major applications of non-circular jets are improved mixing in low and high-speed flows, incremented combustion efficiency, noise suppression, thrust vector control, reduced combustion instabilities, and extended flammability limits[18]. A few problems common to all non-circular jets are axis switching, the azimuthal dependence of the shear layer spreading rate, and turbulence production. The length-to-diameter ratio is an essential factor that changes the injectors' atomization behavior. It is usually noted that no vena-contracta, no cavitation, and no hydraulic flip regime to form within the orifice length. A fully developed flow is required within the orifice length. The importance of the L/D ratio is its influence on the discharge coefficient. As the L/D ratio increases, the coefficient of discharge reduces[19]. Considering the importance of the L/D ratio on injectors with circular orifices, it is believed that the same relation would be applied to non-circular orifices too.

It is observed that the non-circular orifice has various merits over the circular orifice injectors. Thus, attempts have been made in this paper to study the atomization behavior of liquid fuels by using a non-circular orifice that could be used in a liquid rocket application. The relevance of the present study is to reduce the droplet size in order to increase the combustion efficiency of the liquid rocket engine and by means of flow vortices which are self-induced due to the orifice shape. Experimenting with the pressure injectors with a modified shape is an attempt to reduce other supporting systems that are exclusively working to reduce droplet diameters. Various parameters used for the study are its spray cone angle, breakup length, mean droplet diameter, and the Sauter mean diameter. Semi-circular and plus-shaped orifices have been used as non-circular orifices. These results would be further compared with a circular orifice injector. Studies were also conducted with different L/D ratios of the injector by choosing an effective

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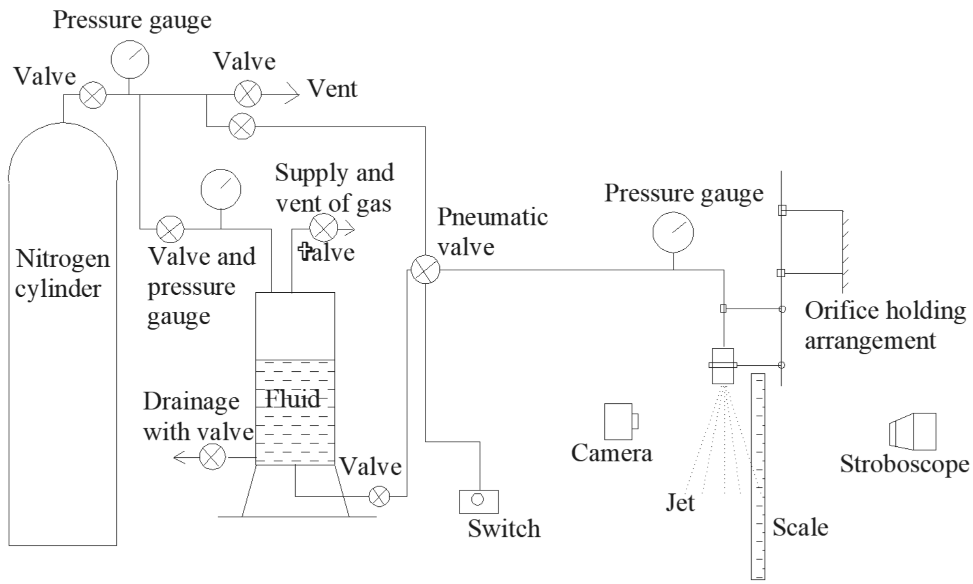


Figure 1. Experimental setup for atomisation studies.

orifice length to reduce upstream losses. The fuel used for the atomization behavior study is Jet A1 fuel.

2. EXPERIMENTAL SETUP AND PROCEDURE

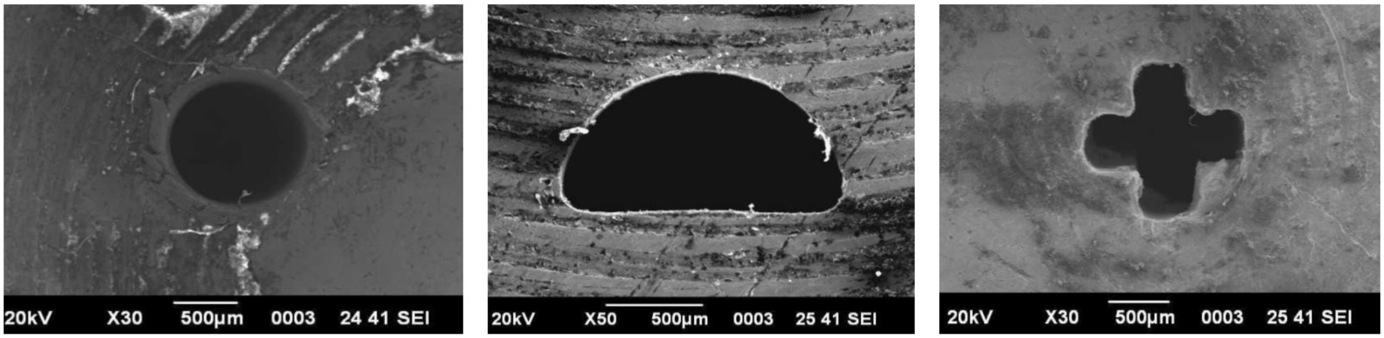
The experimental setup used for the atomization studies of Jet A1 fuel is shown in Fig. 1. It consists of a pressurization system for the actuator pneumatic valve and the fuel tank, feed lines, a test stand, injectors, and a control switch. Initially, nitrogen gas was fed to an actuator valve; this pressurant gas was required to open the actuator valves installed in the fuel injection pipeline. This valve required a minimum of 7 bar pressure to open and close. The fuel tank is utilized to store the fuel. It is pressurized with nitrogen that acts as the pressurant gas. The pressurant gas was supplied through a standard high-pressure pipeline from which nitrogen gas flow was monitored per the requirement to the actuator valve and the fuel tank using an individual control valve. From the fuel tank, the pressurized fuel passes through the feed lines and enters the injector through a ball valve and an actuator valve. The ball valve is provided for safety; if the actuator valve does not work, it could be controlled by the ball valve. The orifice assembly is fixed onto the wall for rigid support to avoid any movement of the injectors during experiments. This arrangement is very essential as the jet is required to be in the vertical position without any action of the jet coming out of the orifice. The wall frame dimensions are fixed, but the injector can be placed at any point within the frame. This fixture enables to capture jet to the scale required and allows any high-pressure jet to hold on without any movement so that the camera's focus is not lost. As non-circular jets are asymmetric jets, this fixture enables to capture at the same scale from all the comers considering no adjustments have been made. The jets coming out of these injectors are captured using a DSLR camera (Nikon D5500) and a stroboscope. The camera was mounted with an actual macro lens of the scale 1:1 and a focal length of 100 mm. A stroboscope is a high pulsating light source combined with a diffuser, providing a light source that flashes on a periodic interval of time. The strobe light enables any object at high speed to freeze instantaneously. Synchronizing these two instruments, the images of the dynamic jets were captured. The pictures that were clicked in a particular resolution are required to be processed.

The camera was set at a maximum shutter speed of 1/4000, meaning it would open its shutter every 250 microseconds. The aperture was also kept at maximum i.e., at F3.5, which means the opening through which the light travels is at maximum. The ISO was kept at 1000. By using a higher ISO, a faster shutter speed could be used to freeze the movement. The stroboscope was set at an RPM of 240000. This means in a minute; the strobe flashes 240000 times. This light flashes every 1 microsecond. This means that the strobe light flashes for every one microsecond duration at the same light intensity. A diffuser is used to diffuse the light coming onto the camera lenses. The diffuser helps in making the light soft and spread it over evenly. This was done so that no sharp light falls onto the camera lens, which eventually gives an image with only beaming light. These images were processed by Image J software[20], a Java-based program developed by the National Institute of Health.

Capturing the jet was done by fixing the jet scale, i.e., the jet's length was 35 cm, and the width was 35 cm. Jets have been further divided into four quadrants to obtain the jet droplets, and the droplets have been captured at those locations using a macro lens and a stroboscope.

3. INJECTOR DESIGN

The design of injectors was done in such a way that there were no upstream losses, and it could sustain high-pressure loads. It was done by the suitable selection of the L/D ratio of the injector and also that it can support high-pressure loads by providing enough wall thickness. The novel shapes considered for non-circular orifice injectors are the semi-circular and the plus-shaped orifices. For simplicity, the injectors were designed in the form of an injector cap so that they can directly fit into the adapter of the feed line so that there are no area changes before entering the nozzle's internal orifice, which



(a) (b) (c)

Figure 2. (a) Circular orifice at a magnification of 30, (b) Semi-circular orifice at a magnification of 50, and (c) Plus orifice at a magnification of 30.

would change the velocity of the flow. Also, another need to fit it directly to the feed is to obtain a fully developed flow and to avoid any air gaps.

The injector orifices were manufactured using the EDM wire cut machining for both injectors, i.e., circular and non-circular orifices. The materials used for making these injectors are brass. The injectors were manufactured with different L/D ratios. For comparison purposes, circular orifices and the non-circular orifice (semi-circular and plus shape orifices) have also been manufactured. The confidence in the accuracy of the orifice shapes and their dimensions, an SEM image has been taken. It is shown in Fig. 2 (a), (b), and (c) with circular, semi-circular, and plus shape orifices, respectively. The image's scale and magnification are also available, along with the figures.

The geometrical dimensions used for the study with circular and non-circular orifices are given in Table 1 and Table 2. Keeping the diameter constant at 1 mm for the circular orifice injector and changing the orifice lengths, the L/D ratios were calculated. As per the prior research on circular and non-circular injectors, it was observed that L/D ratios within 10 have no major losses in the jet[17]. Based on its optimization study presented in the results and discussion section, the L/D ratio for the non-circular orifices has been selected.

Table 1. Geometrical consideration of circular orifice injectors

Orifice diameter (mm)	Area (mm^2)	L/D			
1	0.785	1	4	6	8

Table 2. Geometrical considerations of non-circular orifice injectors

Injector types	Area (mm^2)	Orifice diameter (mm)	L/D
Semi-circular	0.820	1.45	4.1
Plus	0.801	1.20	5.0

The injector orifice areas are maintained close to the area used in the circular orifice to compare circular and non-circular jets. The orifice length for non-circular orifices used was 6 mm; other details are given in Table 2. The reasons for the selection for the 6 mm orifice length would be discussed in the results and discussion section.

4. RESULTS AND DISCUSSIONS

4.1 L/D Characteristics of Circular and Non-Circular Orifice Injector

In the present study, attempts were initially made to select the orifice length of the non-circular orifices. It was done by studying the coefficient of discharge through the circular jets. Water was chosen for this study as the working fluid, and its properties are taken from Ref.[10]. The L/D ratio used for the circular orifice is given in Table 1. The discharge coefficient was calculated with the known properties of water and the mass flow rate through each orifice. The procedure for obtaining these parameters is taken from Ref.[10]. The coefficient of discharge obtained is compared with respect to the Reynolds number. These values are obtained by changing the upstream pressure ranging from 1 to 50 bar in an interval of 7 bar. The results obtained with all the L/D ratio of the circular orifice is given in Fig. 3 (a). It is observed that the 8 L/D ratio has a lower discharge coefficient compared to 1, 4, and 6 L/D. This is because of the frictional losses inside the orifice length. Also, shape adds in for losses in the discharge coefficient. The discharge coefficients for 1 L/D are lower than 4 L/D except in between the Reynold number range of 40,000 to 55,000. This phenomenon is due to the formation of vena contracta inside the orifice length. This 1L/D jet is unstable compared to the jets emerging from L/D of 4 and 6. This phenomenon was also observed by Lichtarowicz, *et al.*[17] with a lower L/D ratio orifice. There is no major change in Cd and Reynolds numbers of 4 L/D and 6 L/D. The change observed is linear, and both 4 and 6 L/D orifices are efficient compared to the 1 and 8 L/D ratios.

Further, an attempt was also made to understand the change of discharge coefficients with respect to the Reynolds number. It is shown in Fig. 3 (b). It is seen that semi-circular orifices give the lowest discharge coefficients compared to other orifices. The uncertainty in the discharge coefficient and Reynolds number measurements were obtained using the Fractional uncertainty analysis as proposed by Taylor[21]. The maximum uncertainty in measuring the discharge coefficient and Reynolds number were 5.2 and 5.7%, respectively. The error percentage in the image processing was around 3%, related to measuring the droplet sizes using image J software.

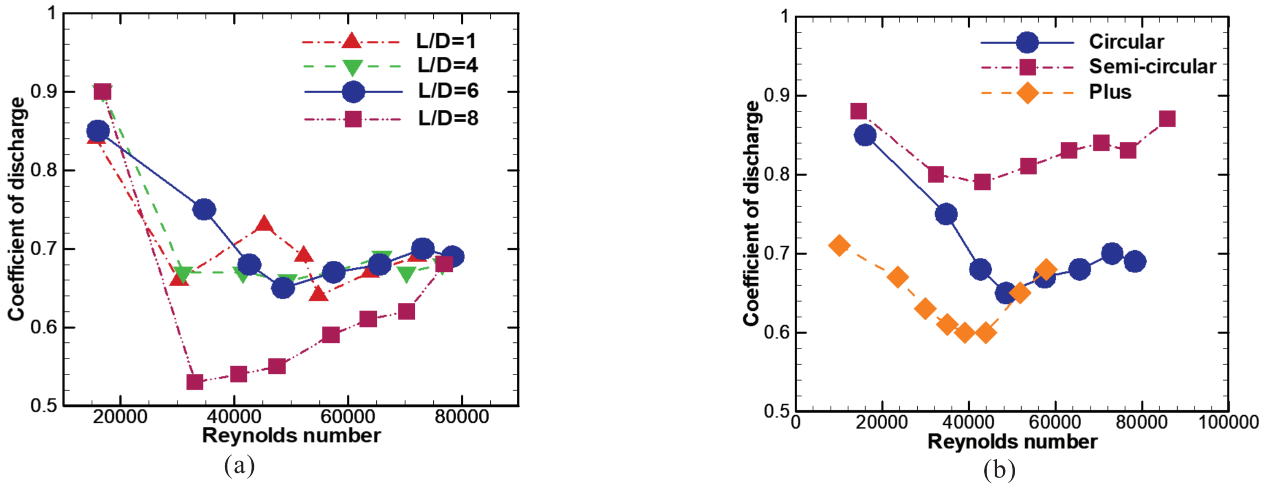


Figure 3. Comparison of discharge coefficients with reynolds number: (a) for different L/D ratios with circular orifice, and (b) for different orifice shapes.

4.2 Atomization Studies Through Circular and Non-Circular Orifice Injectors

The atomization studies are conducted for the types of orifices, i.e., the circular and the non–circular orifices. The L/D ratio used for the circular orifice was 6, while for the semi-circular orifice, it was 4.1, and for the plus orifice, it was 5.

As pressures are increased, the jets break purely due to turbulence. It could also be seen from Ref.[10]. The turbulence was observed in the jet spray that develops due to the breaking of small ligaments into droplets. These droplets are analyzed and measured to determine the atomization efficiency. The smaller the droplets, the larger the droplet's surface area within the jet. Due to high pressure, the droplet size varies and tends to become far more minor. The comparison is obtained between circular and non-circular jets in the present study with their respective L/D ratios considered for atomization studies with respect to their spray cone angle and droplet diameters at each pressure.

4.2.1 Low-Pressure Analysis

The low-pressure studies were conducted at 1 bar. This analysis was done to observe the process of fluid breaking. In the case of non-circular orifices, the axis-switching phenomenon is observed only at low pressures, as reported by Hong et al.[13]. Low-pressure analysis was done for non-circular orifices to capture these phenomena. The jets with the circular orifice was also captured to compare the breakup process between circular and non-circular orifice. The jets were captured up to a length of 60 mm from their orifices' exit for each case. The jet obtained is shown in Fig. 4.

In circular jets, as explained by Gutmark[15] and it is also observed in Fig. 4 (a) that, circular spanwise coherent vortex rings are formed. Spanwise non-uniformities can add complexity to the evolution of the jet shear layer; sufficiently far downstream of the jet exit. Due to the strong streamwise vortices, three-dimensionality analyses of the jet are complicated. The jets emerge from a 6 L/D ratio with a circular injector, which is already turbulent and breaking up from the orifice exit itself. These images are taken with no spatial discontinuity. The jet is shown at 1 bar and is considered within the Rayleigh breakup regime, as observed from Ref.[17].

The images for the semi-circular jet were taken from the orifice's major axis and corner edges. This would enable us to observe the periodic flow changes due to the orifice shape

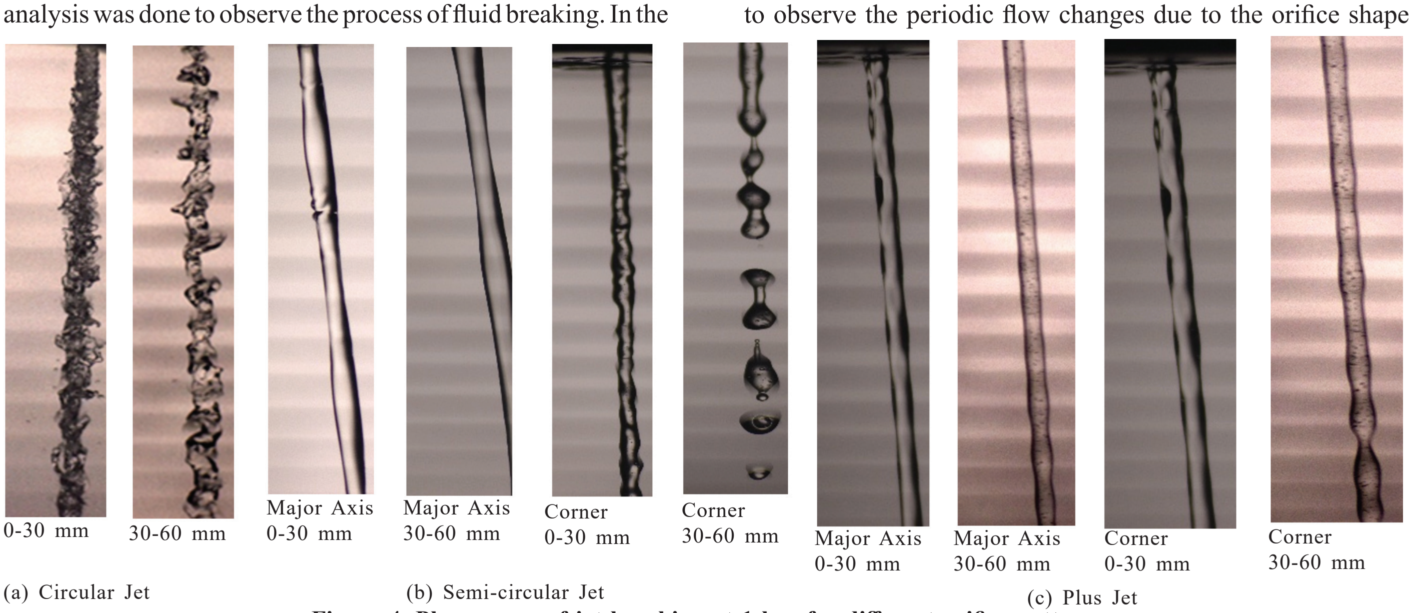


Figure 4. Phenomena of jet breaking at 1 bar for different orifice pattern.

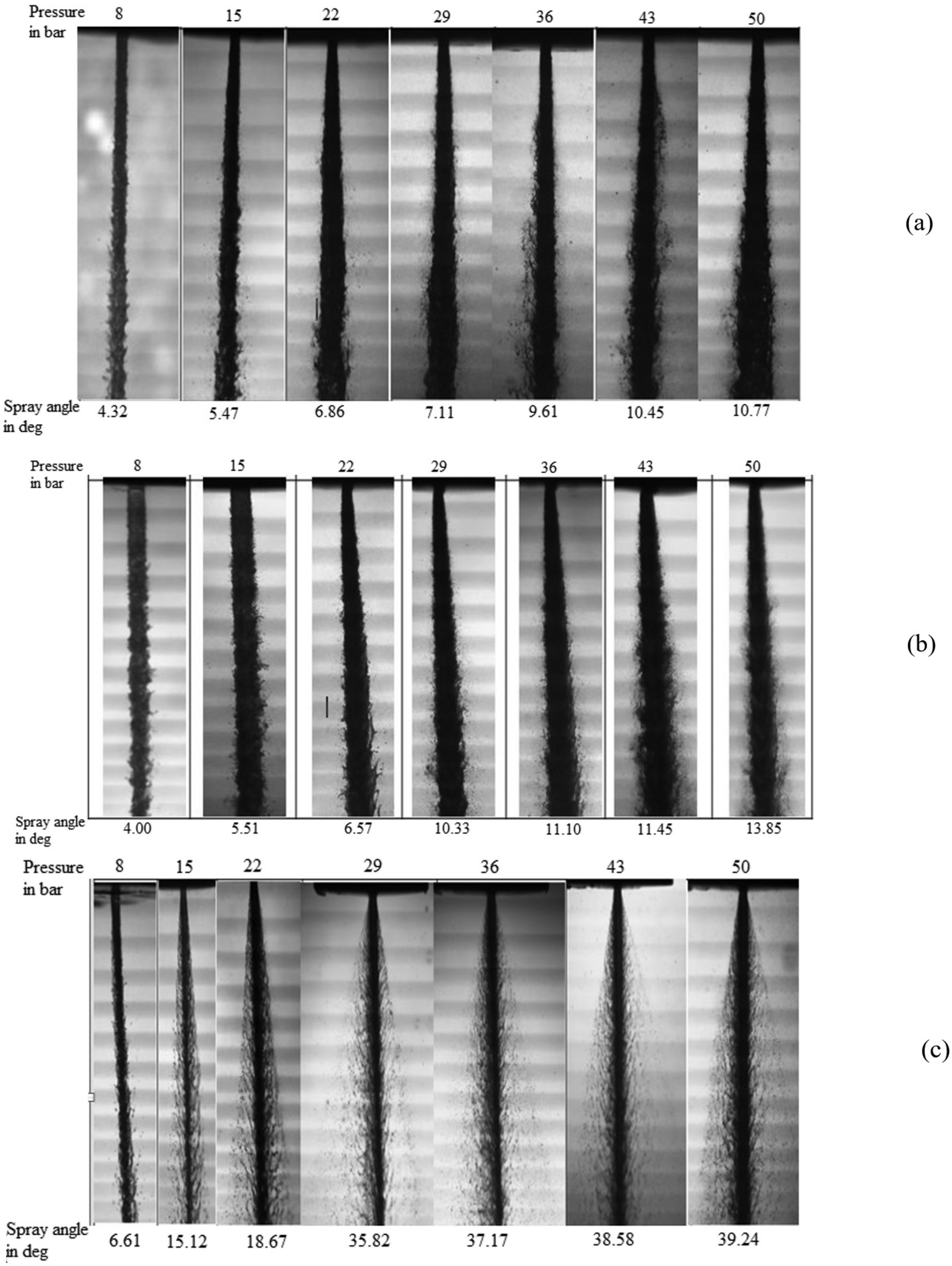


Figure 5. Spray cone angles from: (a) circular orifice injector, (b) semi-circular orifice injector, and (c) plus orifice injector.

change. It is observed from Fig. 4(b) that the semi-circular jet at 1 bar is undergoing axis switching phenomena. The major axis flow turns into a minor axis, and the minor axis flow turns into a major axis. The jet is breaking from a 32 mm distance, as seen in Figure. The droplets are almost spherical. The center line of the jet is similar to a circular jet, and the corners induce vortices. The length of each impinging point at the transition zone is also the same and is measured on an average of 1.36 mm. This twist is observed only in low-velocity flows. Looking at the periodic flow pattern in semi-circular jets it explains that the jet is undergoing axis switching phenomena. This is observed at regular intervals. The jet has developed spanwise and axially vortices, due to which the switching phenomenon is observed. This is purely induced due to the shape of the orifice. The bulged region is the major axis flow, and the thin part is the minor axis flow.

The jet obtained with plus orifice is also shown in Fig. 4(c). It is observed that the jet getting out of the plus orifice are overlapping type of jet, and it is the superimposition of two rectangular jets. At 1 bar, plus jet is switching its axis and rotating about its axis. Both the rectangular jets are turning at the same time, and it is making the flow rotate. Axis switching from one rectangular jet is superimposed onto the other rectangular jet. This can also be explained as the overlapping of two switches at the same time. Plus jets have smaller switch lengths as compared with semi-circular jets. The switch lengths cannot be determined as plus jet is highly three-dimensional. The centerline of the jet is circular with corners of the edges of plus, inducing instabilities into the core jet.

Hence, it is seen from the above studies that both non-circular jets undergo axis switching phenomena and induce turbulence to the jets to break faster solely due to the orifice shape. These phenomena of causing turbulence and breaking the jet faster help to enhance the mixing process between fuel and oxidizer of the liquid rocket engine and enhance combustion efficiency. It would also lead to the overall reduction of the combustor length of the liquid rocket engine, which is beneficial from the weight reduction and the system's reduced cooling requirement.

4.2.2 High-Pressure Analysis

It is known that the higher the cone angle, the higher the atomization of the jet. Thus, in the present study, the spray cone angle is measured directly using the Image J software[20]. It is essential to capture the jets of a non-circular orifice from all sides and corners due to the formation of three-dimensional jets. The captured spray image was converted into grayscale in the Image J software to get the spray cone angle. Then the axial mid-point was taken as the reference and is also considered the center of the orifice. In the grayscale image, the creased edge lines were selected from each corner, and then a volume was created. The spray cone angle was then measured by selecting two points at the end of each jet concerning its field of view to the centerline of the jet. The jet's cone angles are measured up to 30 mm from the orifice exit. The cone angles are measured for all the orifices in the pressure ranging from 8 to 50 bar. It is shown in 5 (a), (b), and (c).

Plain atomizers generally have circular orifices, and their spray cone angles range from 5 to 15 degrees. A well-atomized spray has cone angles above 30 degrees. Taking this data as reference, the spray cone angles are measured with the circular orifice of 6 L/D ratio and having a diameter orifice of 1 mm. The pressure values at which the jets were obtained are indicated at the top of the figures, and the measured spray cone angle is at its bottom.

It is observed that the cone angles for circular orifices range from 4.32 to 10.77 degrees. It comes under the range of 5 to 15 degrees of spray cone angle. It is also observed that the spray is not uniform in all directions. The jet is turbulent and is breaking faster from within the orifice itself, but the droplets spray in the near field from the centerline of the jet. The jet is concentrated due to the series of spanwise coherent vortex rings and their sequential merging. This behavior stops the shear layer growth along the axial length. The jet obtained with this orifice is not well atomized.

After measuring spray cone angles for circular orifices, experiments were also conducted with the non-circular orifice. The semi-circular orifice has a diameter of 1.45 mm and an L/D ratio of 4.1. The spray cone angle obtained with a semi-circular orifice at different pressure ranges is given in Fig. 5 (b). It is observed that the cone angles range from 4 to 14.0 degrees for this orifice. The spray cone angle for the semi-circular jet has increased by 3 degrees compared to the circular jets. The spray is broader and, at the same time, has uniform spray along the axial length. This is due to spanwise and axial vortices interacting, making the jet rotate about its axis. This development of the jet leads to a three-dimensional flow breakup in the jet. It is observed that these jets have fragile ligaments and are breaking faster. The jets have a significant fuel concentration in their centerline.

The plus orifice has a diameter of 1.2 mm and an L/D ratio of 5. The spray cone angle obtained with this injector is shown in Fig. 5 (c). The spray cone angles of these jets are observed to range from 6 to 39 degrees. It is also observed that there are two rectangular liquid sheets that are slicing each other and, at the same time, twisting in their axis. The jet is spreading uniformly along the axial length. The jet's centerline is thin compared to both circular and semi-circular jets. Ligaments are ejecting out of the centerline as the flow is rotating. The entrainment of surrounding gas and mixing would be highly improved in this jet.

It is also to be noted that the spray cone angle improvement with semi-circular and circular orifices is nearly the same upto the injection pressure of 22 bar. Beyond this, pressure improvement with a semi-circular orifice is more significant than with a circular orifice. This study indicates that with a change in the orifice shape alone, the spray quality could be enhanced. Taking circular spray as the reference, semi-circular jet cone angles have shown an improvement of 30%, and jets have improved by 290 percent. This enhanced cone angle of the plus orifice could effectively be used in enhancing the efficiency of the liquid rocket engine.

Apart from it, an attempt was also made to get the Weber number of both the non-circular orifices. It was further compared with the circular orifices. The Weber number has been obtained with respect to the velocity through the orifices, and it is plotted as shown in Fig. 6. It is seen from Fig. 6 that as the velocity increases, the Weber number increases. The jet with higher deforming inertial force overcomes its cohesive force faster and breakdown the jet into fine ligaments sooner. This provides information about the jets through which the jet breaks up easily. The weber numbers of the semi-circular jet are higher than circular and plus jets, as shown in Fig. 6. This means the breakup of the semi-circular jet is faster than the circular one. The breakup length of the semi-circular shape is smaller than other orifices. Plus orifice has a lower weber number compared to circular and semi-circular. It is due to the physics of its orifice geometry.

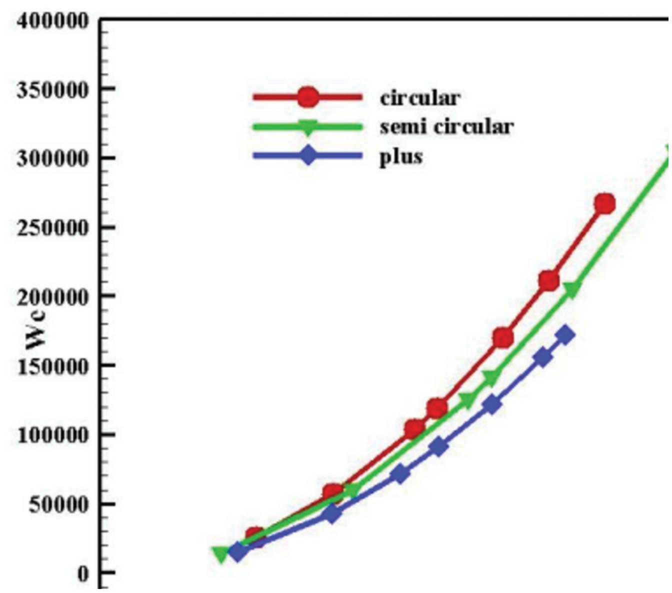


Figure 6. Comparison of Weber numbers with varying velocity for all three non-circular orifices.

4.2.3 Droplet Analysis

Once the spray cone angle is known, it is essential to characterize their droplets. Thus, the mean droplet diameter and their Sauter mean diameter were obtained. For this study, the jet having droplets coming out through circular and non-circular orifice were captured from the orifice exit to the length of 60 mm. The droplets were measured using Image J software by making grids of the spray, and finally, it was enabled to measure the droplets' sizes. This software enables obtaining the areas of the droplet by thresholding technique. Firstly, the images of the 24-megapixel resolution were converted into 16 bit images. A reference scale was given to the image software for measuring the droplets. The scale of the image was also set. The software measures the distance in pixel units. The known measurement value was given as input, and the measurement unit was set to mm. Now, the regions were selected whose droplets are required to be measured. Those images were duplicated and saved. Onto these specific region images thresholding technique was applied to analyze droplet particles. In thresholding, the regions where the jet and the droplets are present were highlighted with black color. The images' thresholding was done manually to shade only the droplets alone. After the thresholding process was completed, the particle analysis was done. In this, the droplet size range was kept from 0 – infinity. The circularity was maintained from 0.9 to 1. Circularity 1 means that the shape of the droplet is a perfect circle. If it is 0.0, the shape is an elongated polygon. The outline of these droplets was given by the software. The measurements were saved in the excel sheet. The droplet areas have been obtained for the number of droplets that emerged for that circularity. From these areas, the diameter of the droplets was obtained. These processes were repeated for all the pressure conditions ranging from 22 to 50 bar. The results obtained for mean droplet diameter and sauter mean diameter is shown in Fig. 7(a) and (b), respectively.

It is seen from Fig. 7(a) that the circular jets have larger mean droplet diameters as compared to the non–circular jets. Semi-circular jet has lower mean droplet diameters as compared with circular droplets but has non-uniform decrement in mean droplet diameter with the increase in the pressure and a similar pattern was also observed with the plus orifice mean droplet diameters.

The reason for this is that at certain pressures, due to droplet diameters being dependent on the axial location of the jet, the droplets tend to agglomerate and form a larger droplet. It further goes through the secondary breakup that tends to decrease the droplet diameters additionally. Hence, it can be stated that the non-circular orifice gives a jet of smaller mean droplet diameters as compared to that obtained with the circular orifice. Due to the non-circular nature of the orifice, fine spray and smaller droplet sizes were obtained with the plus orifice. Thus, it is expected that the combustion efficiency of

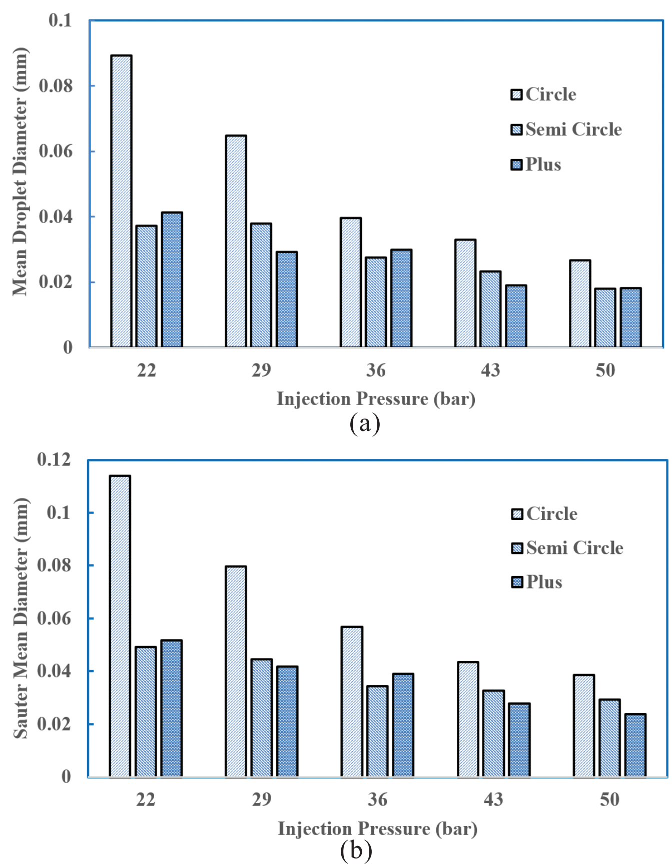


Figure 7. (a) Mean droplet diameters (b) Sauter mean droplet diameters of circular and non-circular droplets in mm.

the liquid rocket engine will improve with the use of this type of injector.

From Fig. 7(b), it is observed that the circular orifice gives a larger Sauter mean diameter compared to the non-circular orifice. Semi-circular and plus orifice jet gives varying Sauter mean diameter at different pressures, but it is in the decreasing trend. This is due to the droplets being dependent on the time of capturing, location and breaking process. At any instant, the droplet suddenly increases due to the coalescence of many droplets. Further, the secondary breakup takes place and the droplet diameter becomes smaller again. The variation is not very high; it is of the order of a few microns. Hence, the droplets jetting out of non-circular orifice have smaller droplet diameters compared to circular orifice jets.

5. CONCLUSION

The present study deals with the atomization studies with the pressure jet types of the injectors where two types of orifices have been selected, i.e., circular and non-circular orifices. The semi-circle and plus shapes were used as the non-circular orifice. These studies were conducted at a pressure ranging from 1 to 50 bar. The main parameters used for the studies include the Reynolds number, spray cone angle, mean droplet diameter and the Sauter mean diameters.

From the studies, it was observed that for an efficient injector, the orifice lengths of the injectors for circular and non-circular orifices should be below the 8 L/D ratio. The semi-circular and plus jets were turbulent, but the semi-circular jets were unstable, while plus jets were stable. It was due to the difference in the Reynolds number. It was also seen that the semi-circular and plus jets both undergo axis switching phenomena, leading to the flow twisting in its own axis. The spray cone angles of the plus and semi-circular jet have increased by 290 % and 30 %, respectively, compared to the circular spray cone angles. The mean droplet diameters are larger for circular jets and smaller for non-circular jets. The mean droplet diameters among semi-circular and plus jets tend to vary based on their location and pressures. The Sauter mean diameters of non-circular jets are low compared to circular jets. The Sauter mean diameter among semi-circular and plus jets tends to increase and decrease due to the coalescence phenomena.

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