SHARMA, PRIYESH. Breakup of Liquid Jets and Spray Characteristics of Diesel Fuel from Non-Circular Orifices. (Under the direction of Dr. Tiegang Fang).

In view of the stringent emission regulations and depleting fossil resources, improving the combustion efficiency and lowering the exhaust emissions of internal combustion engines is monumental. Spray combustion is primarily governed by the fuel atomization process. High injection pressures and small nozzle orifice diameters are employed to achieve fine atomization and better air fuel mixing in the engines. However, increasing injection pressures imposes greater loads on the fuel injection systems and requires precise manufacturing, thus, is a costly affair.

In an attempt of seeking techniques for improving the fuel atomization process, we have tested the spray characteristics obtained from non-circular orifices. For a better understanding of the underlying processes, analysis was carried out on low pressure water jets as well as high pressure diesel sprays obtained from rectangular, square and triangular geometries and compared with the corresponding jets and sprays obtained from circular orifices of similar cross-sectional areas. The low pressure analysis was carried out for gauge pressures varying from 0 psi to 1000 psi while the high pressure analysis used a common rail diesel injection system discharging the fuel at pressures from 300 to 1000 bars.

To draw a comparison between the circular and non-circular jets and sprays, properties including the breakup length, jet width and droplet size were measured for the low pressure jets. For the high pressure sprays, properties like spray width, cone angle, tip...
penetration, velocity and acceleration and volume have been measured. The measurements were made by processing the digital images obtained using a high speed video camera. A laser diffraction particle analyzing system from Malvern was used to measure the droplet size obtained from the sprays of different geometries. The measurements were carried out at different axial locations along the spray axis.

The jets and sprays were discharged into the ambient gas at room temperature and pressure conditions. While for the images captured by the high speed camera the liquids were injected in the vertical direction, for the droplet size measurements diesel fuel was sprayed in the horizontal direction. The flow characteristics were analyzed from different directions, including looking at the flow from the straight edges of the orifices as well as their sharp corners.

The non-circular geometric jets and sprays demonstrated enhanced instability as compared to the circular jets and sprays. This has been attributed to the axis switching phenomenon exhibited by them. Due to axis switching the non-circular jets and sprays change their spatial orientation periodically along the axial direction and also acquire circular cross sections during the process. As a result, the non-circular jets yielded shorter breakup lengths as compared to the circular jets. In order to demonstrate the presence of axis switching phenomenon in square and triangular jets and high pressure diesel sprays, the jet and spray widths were plotted along the axial direction. This technique proved very useful and clearly demonstrated the axis switching occurring in square and triangular jets which was not clearly visible as in the case of rectangular jets.
High pressure diesel sprays obtained from non–circular orifices exhibited larger widths and hence, larger surface areas, greater cone angles, better penetration and hence, larger spray volumes than the circular sprays. In short, non-circular geometric shapes achieved better air entrainment and hence, mixing than the circular sprays. The droplet size obtained depends on the location of measurement and injection pressure and different behaviors are observed at different locations.

Thus, it was observed that the non–circular orifice geometry induces greater instabilities in the jets and the sprays thereby leading to their faster disintegration. As a result, an improvement in the spray characteristics can be achieved using the non-circular geometries. Axis switching phenomenon plays a key role in improving the spray characteristics. To conclude, the non–circular geometry provides a cost effective technique for passively controlling the flow characteristics.
DEDICATED

To my family for their unconditional love, affection and motivation which always pushed me to perform better
BIOGRAPHY

Priyesh Sharma was born on October 21, 1986 in the holy city of Ajmer, Rajasthan; in north western India. He completed his schooling from Mayoor School, Ajmer. Seeking a holistic development as an engineer he joined BS in Marine Engineering program of Birla Institute of Technology & Science, Pilani, Rajasthan. The interdisciplinary curriculum of Marine Engineering and work experience in Chevron Shipping gave him the opportunity of gaining hands-on experience of working on marine diesel engines. Pursuing his interests in the field of internal combustion engines he went on to join the North Carolina State University, Raleigh in Fall 2011. In the Department of Mechanical & Aerospace Engineering, he joined the research group of Dr. Tiegang Fang. His research work mainly focused on the spray characteristics of diesel fuel and high pressure fuel injection systems. He finished his Masters in December, 2012 with the intention of making positive contributions in the field of internal combustion engines.
ACKNOWLEDGMENTS

I owe my profound gratitude to Dr. Tiegang Fang for giving me the opportunity of joining his research group. I gladly appreciate his support, encouragement and patience. Without his inspiration and guidance, this work would have not been possible. I consider myself very fortunate to get the opportunity of working under him.

I would also like to express my gratitude to Dr. William Roberts and Dr. Alexei Saveliev for taking out time from their schedule to be a part of my thesis committee.

I am thankful for the support I received from Ms. Annie Erwin. Special thanks to Mr. Rufus Richardson (Skip) for providing the technical support and finishing all the machine shop requests within short periods of time even when given on short notices.

Thanks to Wei Jing, J R Archer, Dolanimi Ogunkoya, Sandesh Saokar and Suman Basu for their immense support. Wei and J R provided unconditional help despite of their busy schedules. Best regards to Amruth Kiran Hegde and Pravin Dandin for their friendly support during the research work.

All this would have not been possible without the love, support and motivation I received from my family. I wish to live up to their expectations.

This research was supported in part by the Research and Innovation Seed Funding (RISF) program from the North Carolina State University and by the Natural Science Foundation under Grant No. CBET-0854174.
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CHAPTER 1: INTRODUCTION

The essence of a diesel engine is the introduction of finely atomized fuel into the air compressed in the cylinder during the compression stroke. Fuel atomization plays an important role as reduction in mean fuel drop size increases volumetric heat release rates, lowers exhaust concentrations of pollutant emissions [1-3] and determines the combustion efficiency, power output and fuel economy of an internal combustion engine. For the complete combustion of the fuel at the correct time it is necessary that it breaks down into tiny droplets for better heat transfer and rapid evaporation. These tiny droplets should also be able to penetrate deep enough in the combustion chamber in order to ensure proper mixing with air / oxygen. Primarily, most engines use high pressure fuel injection with small orifices for achieving better atomization and reducing NOx and particulate emissions [6]. Some recent engine designs achieve as much as 2300 bar injection pressure when pumping inferior quality fuels like heavy fuel oil. Various other techniques like air blast injection, using compressed air for fuel atomization, were used earlier but they had their own limitations. With the development of materials capable of withstanding greater pressure and fatigue loads safely, direct injection (DI) has emerged as the dominant principle in modern medium and high speed engines. In (DI) engines, fuel atomization and air / fuel mixing are achieved by the energy in the fuel spray injected at very high pressure. Additional mixing may be achieved by the orderly movement of the air in the combustion chamber, which is called ‘air swirl’. Naturally aspirated engines usually have a degree of swirl and an injection pressure of around 800 bars. Highly turbocharged heavy duty engines with four-valve heads have
virtually no swirl, and have to employ injection pressures of 1200–1800 bars to provide the mixing energy [4].

Further improvements in fuel atomization cannot be achieved by increasing injection pressures and reducing orifice size only. Higher pressures impose limitations on the safe working loads of the engine fuel injection system and precise manufacturing thereby increasing the equipment cost. Further, smaller orifices are difficult to manufacture and are prone to blockage. This calls for looking at the basics of the atomization process.

Atomization is one of the different modes of the liquid jet breakup. The breakup of a liquid jet emanating from an orifice is an ubiquitous phenomenon of nature with its application related not only to spray and droplet formation in combustion engines but also in fields of medical aerosols, low pressure plasma deposition, modified gas welding techniques, high velocity oxy-fuel thermal spraying to name a few [31].

Liquid jet breakup is not a simple process and is influenced by a large number of parameters including the details of the design of the nozzle, the jet’s velocity and turbulence, and the physical and thermal states of both liquid and surrounding gas [16 - 18]. As jets are discharged from an orifice they are subjected to a destabilization process which causes the breakup of the jet. The destabilization process may originate from the disturbance waves on the jet surface, initiated within the nozzle due to its geometry and / or cavitation or at the orifice exit owing to inertia and aerodynamic forces. Two major features to characterize the destabilization process are the breakup length of the jet, which is defined as the length of the jet from the nozzle tip to first drop break up, and the droplet size. These two parameters define the regime of the jet breakup. So far, the research on liquid jet breakup has
concentrated majorly on circular orifices though there has been interest in studying the effect of asymmetric orifices since the nineteenth century. Rayleigh [5] analyzed the experimental works of Bidone [6] and reported the axis–switching phenomenon observed in jets issued from non-circular orifices. Due to this phenomenon, liquid jets issued from elliptical orifices lose their ellipticity at increasing distances from the orifice and further out the ellipticity is regained but the orientation of major and minor axes is switched by right angles. The phenomenon is periodic along the jet axis. The unique behavior of jets issued from non-circular orifices introduces further hydrodynamic instabilities which significantly influence the jet breakup. Results of the investigations on jets issued from non-circular orifices show that non-circular geometry of the orifice tends to provide an efficient technique of passive flow control at a relatively cheaper cost as it involves changes in the geometry of the nozzle only.

This work experimentally investigates the effect of asymmetric nozzle geometry on the breakup phenomenon of water jets issued at pressures as low as a few psi and spray characteristics of Diesel fuel at pressures as high as 1000 bars. It mainly focuses on the asymmetric geometries with corners – rectangle, square and triangle. The rectangular orifice also has aspect ratio effects similar to an elliptical orifice. Owing to difficulty in the manufacturing process and costs involved elliptical orifice could not be covered in this work. The experiments were conducted in two stages. Firstly, the breakup and axis–switching phenomena have been studied for water jets emanating at low pressures from 0 to 1000 psi from non-circular orifices like rectangle, square and triangle and compared with the results obtained from a circular orifice. Injection pressure of 0 psi means that the fluid was allowed
to fall freely under the effect of gravity and hydrostatic pressure of the liquid column and no external pressure were applied. In the second stage, a high pressure common rail diesel injection setup was prepared to inject diesel fuel from a single-hole nozzle at pressures ranging from 300 – 1000 bars. The nozzles used had non – circular geometry (rectangular, square and triangular) and the results were compared with the spray characteristics of a circular orifice. In each stage, the jets and the sprays were discharged into quiescent air background. Care was taken to ensure that the non - circular orifices had the cross sectional area approximately equal to the corresponding circular orifice.
CHAPTER 2: LITERATURE REVIEW

Circular orifice

Disintegration of liquid jets

The earliest investigations of the breakup of a liquid jet emanating into another fluid dates back more than a century. In 1829, Bidone [7] studied the geometric forms of jets produced by nozzles with non-circular orifices while Savart, 1833 [8], was the first to quantitatively describe the jet disintegration process. He suggested that if the jet diameter is kept constant, the breakup length is directly proportional to the jet exit velocity and for constant jet velocity; the jet length is directly proportional to the orifice diameter. Plateau [9] demonstrated that the surface energy of a uniform circular cylindrical jet is not the minimum attainable for a given jet volume. He suggested that the jet tends to break into segments of equal length, each of which is $2\pi$ 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. By neglecting the effects of ambient gas density, jet liquid viscosity and the gravitational forces, Rayleigh [10] demonstrated that a cylindrical laminar jet issued in still air is unstable with respect to the disturbances of wavelengths larger than the jet circumference. He calculated the potential energy of the disturbed configuration relative to the equilibrium value as

$$E_s = \frac{\pi \sigma}{2d} (\gamma^2 + n^2 - 1)b_n^2$$  \hspace{1cm} (2.1)

where, $E_s =$ potential surface energy

$d =$ jet diameter
\( b_n = \) constant in Fourier series expansion
\( \gamma = \) dimensionless wave number \( = 2\pi/\lambda \)
\( \lambda = \) wavelength of disturbance
\( n = \) any positive number including zero.

For non symmetrical disturbances, \( n >> 1 \) and \( E_s \) is always positive, indicating that the system is always stable to this class of disturbance. When \( n = 0 \) and \( \gamma < 1 \), which is the case for symmetrical disturbances, shows that the \( E_s \) is negative and the system is unstable to this class of disturbance. Hence, a liquid jet that is affected by surface tension forces only will become unstable to any axisymmetrical disturbance whose wavelength satisfies the inequality

\[
\lambda > \pi d
\]

which corresponds to

\[
\gamma < 1
\]

Thus, according to Rayleigh, for non viscous liquid jets under laminar flow conditions all disturbances on the jets with wavelengths greater than its circumference will grow. Among all unstable disturbances, the jet is most susceptible to disturbances with wavelengths 143.7% of its circumference or,

\[
\lambda_{opt} = 4.51d
\]

where, \( \lambda_{opt} \) is the optimal wavelength corresponding to the exponential growth rate of fastest growing disturbance.

After break up, the cylinder of length \( 4.51d \) becomes a spherical drop, so that
4.51d \times \frac{\pi}{4} d^2 = \left(\frac{\pi}{6}\right) D^3  \tag{2.5}

and hence,

Drop diameter, D = 1.89d \approx 2d  \tag{2.6}

Thus, for Rayleigh mechanism of break up the average drop size is nearly twice the diameter of the undisturbed jet. Figure 2.1 shows an example of Rayleigh jet breakup mechanism.

These predictions of Raleigh’s mathematical analysis were later confirmed by Tyler [11] who experimentally showed the following results:

\[
\frac{D}{d} = \left(1.5 \frac{\lambda}{d}\right)^3 \tag{2.7}
\]

\[
\lambda_{\text{opt}} = 4.69 \, d \tag{2.8}
\]

\[
D = 1.92d \tag{2.9}
\]
He, thus, concluded that the cylindrical jets break up under the condition required for maximum instability, as predicted by Rayleigh’s theory. Weber [12] extended the works of Rayleigh to viscous liquids and also included the effects of ambient gas density. But, his theoretical predictions did not agree well with the experimental data as pointed out by Sterling & Sleicher [13]. Chandrasekhar [14] showed mathematically that the minimum wavelength for jet breakup is same for both viscous and non-viscous liquids, but the optimum wavelength is greater for viscous liquids and that the effect of relative air velocity is to reduce the optimum wavelength for jet break up. He also showed that the physical mechanism of the breakup of a viscous liquid jet in a vacuum is capillary pinching. Taylor [15] also emphasized on the importance of ambient gas density on the form of jet breakup. For cases, where the ambient gas inertia force, which is directly proportional to the ambient gas density, is very large as compared to the surface tension force per unit of interfacial surface area, the jet disintegrates at the liquid-gas interface into droplets with diameters much smaller than its own diameter. This mode of breakup refers to atomization where the jet breaks into a fine spray.

**Breakup regimes**

After rigorous experimental investigations and the qualitative descriptions obtained from the linear stability theory, the disintegration of a liquid jet can now be classified into distinct regimes of breakup. The different regimes are characterized by the appearance of the jet depending upon the operating conditions. The regimes are due to the action of dominant forces on the jet, leading to its breakup, and it is important that these forces be identified in order to explain the breakup mechanism in each regime [19]. A cylindrical liquid jet
emanated in stagnant gas undergoes four different breakup regimes depending on the interaction of the liquid inertia, surface tension, and aerodynamic forces acting on the jet. The different regimes of jet breakup can be schematically shown on a plot of varying breakup length of the jet as a function of jet velocity, keeping all other parameters constant as reviewed by Grant and Middleman [20]. This is shown in Figure 2.2.

In order to form a jet, the liquid must have sufficient momentum else it is discharged in the form of dripping drops. Once the initial momentum is gained (point C), the jet breakup length increases linearly with the jet velocity. This linear variation (CD) of the breakup length with jet velocity corresponds to the Rayleigh jet breakup mechanism. This is caused by the growth of asymmetric oscillations on the jet surface, induced by surface tension. Drop
diameters exceed the jet diameter as predicted by Rayleigh. Thereafter, the curve reaches a peak (point E) and then decreases. This regime is termed as the first – wind induced regime. Here, the surface tension effect is augmented by the relative velocity between the jet and the ambient gas, which produces a static pressure distribution across the jet, thereby accelerating the break up process. Similar to Regime 1, the breakup takes place many jet diameters downstream of the nozzle. The drops are pinched off from the jet and their sizes are comparable to the jet diameter [21]. For higher jet velocities, the nature of the breakup curve remains controversial. According to Haenlein [22], the breakup curve remains constant or decreases slightly with increasing velocity (FG) and then it abruptly reduces to near zero. However, as per the works of McCarthy and Malloy [32] and Grant and Middleman [20] the breakup length initially increases (FH). These two behaviors of the breakup curve indicate existence of two distinct regimes in the jet breakup. As per Reitz and Bracco [23], at sufficiently high jet velocities, jet surface disruption occurs prior to the jet core. Hence, they have defined, two different breakup lengths, the intact – surface length and the intact – core length, to clearly demarcate the two phenomena. In Rayleigh and first wind-induced regimes, the jet breaks up simultaneously over the entire cross section and hence, the two lengths coincide. The high jet velocity regime, where the jet disruption initiates at the surface and eventually reaches the core the intact – surface length is different from the intact – core length. This regime is called the second wind-induced regime. Owing to high relative velocity between the jet and the ambient gas, the jet is subjected to short wavelength and thus, high energy surface waves. This wave growth is opposed by the surface tension. Jet
disintegrates several diameters downstream the nozzle and the average drop diameter is much smaller than the jet diameter.

Figure 2-3 Schematic representation of the jet breakup length, \( L_b \), jet intact – core length, \( L_c \) and the intact – surface length, \( L_s \). \( \Lambda \) is the wavelength of the induced surface perturbations. *Source: Lin and Reitz [25]*

The regime where the intact-surface length becomes zero (though the intact-core length may not necessarily be zero) is identified as the atomization regime [23]. The breakup curve follows the trend suggested by Haenlein [22], viz. the breakup length drops to zero. Here, the jet disrupts completely at the liquid-gas interface and the drops formed are much smaller than the jet diameter. So far, the disruption of the jet at higher jet velocities has been attributed to the effect of surrounding gas. However, Phinney [28] explained the occurrence of the peak by considering the initial disturbance level of the jet as a variable contrary to the traditional concept of constant initial disturbance level. The initial disturbance level is known to vary with the relaxation of jet velocity profile at the orifice exit, the ambient gas density and the fluid viscosity effects [13, 29]. Relaxation of the jet velocity is the process by which the
velocity profile of a laminar jet inside an orifice rearranges to the uniform or plug flow profile because of the cessation of the solid boundary [23, 30]. As soon as the jet leaves the nozzle orifice, there exists no physical constraint of the nozzle wall; as a result, momentum transfer between the transverse layers of the jet takes place leading to velocity profile relaxation [31].

Figure 2-4 Relaxation of Laminar velocity profile as suggested by [23, 30].

McCarthy and Malloy [32], defined a quantity, $\epsilon$, the ratio of the kinetic energy of the fluid flow to the equivalent kinetic energy under plug flow conditions, such that

$$\epsilon = \int_0^A \frac{U_r^2 dA}{U^3 A}$$  \hspace{1cm} (2.10)

where, $U_r$ is the local fluid velocity and $U$ the average fluid velocity over area. For three different flow situations we have

- For plug flow, $\epsilon = 1$.
- For fully developed turbulent flow, $\epsilon = 1.1$ to 1.2.
- For fully developed laminar flow, $\epsilon = 2.0$. 

When a fully developed flow emerges from a nozzle, its parabolic profile relaxes into a flat profile at the same average velocity as shown in Figure 2-3. This process is accompanied by a reduction in $\epsilon$ from 2 to 1 that involves a considerable redistribution of energy within the jet, thereby bringing to the jet surface liquid particles with radial velocity components and thus, leading to the creation of forces that can be quite violent, causing the jet to burst. This phenomenon of “bursting breakup” was also explained and noted by Eisenklam and Hooper [33] and Rupe [34]. Thus, in addition to the normal jet destabilizing forces, there is present an additional disruptive mechanism arising from the internal motions associated with velocity profile relaxation. Turbulent profiles with $\epsilon = 1.1$ to 1.2 are only slightly susceptible to the profile relaxation effects. However, turbulence produces ruffles on the jet surface thereby making it more susceptible to the aerodynamic forces. Due to the distinct roles played by turbulence and aerodynamic forces, the atomization process is classified as *primary atomization* where the jet breakup is the result of the internal forces like turbulence, inertial effects, or velocity relaxation effects and *secondary atomization* which also involves aerodynamic forces in addition to the internal forces [31]. Secondary atomization or aerodynamic forces act directly on the jet surface and are responsible for the breakdown of drops formed in primary atomization into smaller droplets.
The behavior of the jet in different regimes is shown in Figure 2.2. For given inlet condition, different physical mechanisms are active in the different breakup regimes. In each regime different physical forces play a dominant role in the breakup. The relevant physical forces include the surface tension, the inertial forces in the liquid and the surrounding gas, the viscous forces and the body force. The relative importance of these forces are determined by the Weber number, Reynolds number, Froude number, Mach number, density ratios and velocity of the fluids involved [23, 24]. Although the behavior shown is with respect to the jet velocity, the nozzle internal design effects play an important role, especially for high speed jet breakup. High speed liquid jets are used extensively in jet cutting applications and they remain intact for a distance of many diameters away from the nozzle. On the other hand,
under similar injection conditions, the fuel injected from modern diesel injection systems undergo rapid atomization. The significant difference in the two jet behavior is the result of differences in the nozzle interior design features. Diesel nozzles are typically short-length holes with sharp edged inlets, whereas jet cutting nozzles are contoured nozzles with minimal initial disturbances to the liquid flow [25].

The criteria for demarcating the different regimes of a cylindrical liquid jet emanated in still air have been numerically quantified. By balancing the liquid inertia force and the surface tension force of a free liquid column Ranz [26] determined that dripping no longer occurs and formation of jet occurs if jet liquid Weber number, \( We_L > 8 \), where \( We_L = \frac{\rho_L U^2 D}{\sigma} \). The criterion ambient gas Weber number \( We_G = \frac{\rho_G U^2 D}{\sigma} < 0.4 \) corresponds to the point where the inertia force of the surrounding gas reaches about 10% of the surface tension forces. \( \rho_L \) and \( \rho_G \) are the liquid and gas densities, \( U \) is the jet initial velocity and \( D \) is the orifice diameter. Numerical results of Sterling and Sleicher [13] indicate that the maximum in the jet breakup length occurs when \( We_L = 1.2 + 3.41 Z_L^{0.9} \), where \( Z_L = \frac{We_L^{0.5}}{Re_L} \), \( Re_L = U(D) / \nu_L \).

Thus, it marks the onset of first – wind induced regime. Hence, the criteria for Rayleigh breakup would be

\[
We_L > 8 \text{ and } We_G < 0.4 \text{ or } We_G = 1.2 + 3.41 Z_L^{0.9}. \quad (2.11)
\]

Ranz [26] further argued that the gas inertia is of the same order as the surface tension force when \( We_G = 13 \). This marks the end of the first-wind induced regime. Thus, the limits for the first induced regime are
Thus, \( We_c = 13 \) also indicates the beginning of the second – wind induced regime where the aerodynamic forces start to become dominant. Miesse [27] suggested the criterion for the onset of atomization as \( We_c > 40.3 \).

Hence, the limits for the second-wind induced regime can be defined as

\[
13 < We_c < 40.3
\]

The second – wind induced regime is the last breakup regime where an unbroken section of jet is visible downstream of the nozzle exit. However, none of the criteria mentioned above takes nozzle internal flow effects into account.

**Non – circular orifices**

Till date, majority of the research work has been carried out on the jets issued from circular orifices. Few studies have considered the asymmetrical orifice geometries. However, the interest in non - circular orifices dates back to the days of Bidone [7]. Rayleigh analyzed Bidone’s observations [10] and reported about the unique phenomenon of axis – switching demonstrated by the jets from non - circular orifices. Citing the experiment of Bidone, Rayleigh [35] stated, “Thus in the case of an elliptical aperture, with major axis horizontal, the sections of the jet taken at increasing distances gradually lose their ellipticity until at a certain distance the section is circular. Further out the section again assumes ellipticity, but now with the major axis vertical.” The surface tension force of the liquid is considered responsible for this unique phenomenon. Once the jet is discharged from the elliptical orifice, surface tension tries to minimize the curved surface area of the jet by pulling the ends of major axis inwards and the ends of minor axis outwards. Due to the lateral inertia of the jet,
the movements of major and minor 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 [44]. This geometrical oscillation from elliptical to circular and back to elliptical cross section persists until damped by the viscous forces or the jet breaks up downstream owing to growth of instabilities on its surface.

Rayleigh [36] developed a model to measure the dynamic surface tension using the wavelength of the axis switching phenomenon of an elliptical jet. Bohr [37] further extended the work by taking viscosity into consideration which was neglected by Rayleigh. In his model, he considered finite deviation of the cross section from circularity. Caulk and Naghdi [48] presented a non linear one dimensional model for an elliptic, viscous jet using the basic theory of one – dimensional Cosserat continuum [49]. In [38, 39] Bechtel et al. develop a comprehensive theory of one space dimensional closure models for free viscoelastic free jets based on the assumption that the jet is slender. They used Galerkin averaging method and integrated the Navier – Stokes equation over the jet cross section. Their results resulted in Cosserat equations. The model described in [38] incorporates the effects of elasticity, viscosity, surface tension and gravity. They later used the model for studying the viscoelastic elliptical jets for the special case of a Newtonian free jet with constant surface tension [39, 40] and for the measurement of dynamic surface tension and elongational viscosity [41, 42].
As can be seen, among all the non-circular orifice geometries elliptical orifices have been studied extensively. The elliptical jets present an intermediate case between round and planar jets. The main advantage of elliptical cross section over circular case is that it facilitates rapid mixing and spreading when the liquid is discharged into another fluid [45].

The azimuthal curvature variation in an elliptic jet makes the flow feature very complex. Even in Diesel spray applications, under some experimental conditions, elliptical nozzles have shown better performance than circular nozzles. The elliptic spray angle is much larger than that of the circular spray while the Sauter mean diameter (SMD) of elliptic sprays is much smaller than that of circular sprays [46]. Furthermore, Messina and Acharya [47] studied experimentally the velocity field and spreading rate of a liquid spray issued from an elliptic nozzle with and without primary air. By active control of the air flow, they manipulated the mixing and dispersion of the spray. Their results show that in comparison to a circular nozzle, the spray issued from an elliptic nozzle provides better mixing in terms of higher mass entrainment and greater jet width.

In [43, 44], Kasyap et al. experimentally studied the axis-switching and breakup length of elliptic liquid jets and showed that the elliptic jets exhibit more unstable behavior and hence, have a shorter breakup length than a corresponding circular liquid jet. Furthermore, they discussed the effect of ellipticity on breakup length and showed that increasing the ellipticity in some ranges makes the elliptic liquid jet more unstable.

These results clearly indicate that asymmetric geometry of nozzle orifice provide a very effective passive control over jet breakup phenomenon and introduces enhanced instabilities
thereby reducing breakup length and droplet size and in some cases, improving mass
entrainment by better mixing.

Using the linear form of one – dimensional Cosserat equations, Amini and Dolatabadi [50, 51] carried out the temporal and spatial analysis of wave propagation in viscous liquid jets emanating from elliptic cross section orifices and predicted the jet profile as a function of time and axial space. They validated their results through experimental measurements and were in agreement with the results obtained by Kasyap et al. [44].

Spray characteristics like spray tip velocity, penetration, width, angle intermittency and heat release rate of elliptic nozzles at injection pressures varying from 300 to 1300 bars were studied by Jacobsson, Winkelhofer and Chomiak [61] and were compared with the results obtained from circular and step orifices. They observed substantial differences in the spray characteristics. At low injection pressure of 300 bar, the spray width increased twice as fast in the minor axis plane of the elliptic and step orifice than the circular orifices. Also, the non-circular geometries showed close-to-nozzle spray cone angles in both the minor and major axis planes. The spray cone angle for elliptic minor axis plane was 93% larger than one of the circular orifices used. Moreover, the spray cone angle and spread were larger in the minor axis plane than the major axis plane for the elliptic nozzle, and the spray became circular at around 25 mm from the nozzle tip. However, at injection pressures beyond 500 bars no significant effects of differences in the orifice geometries were observed. Also, even though the spray characteristics differed at low injection pressures, heat release rates were different for the different geometries at only 300 bars.
Xi et al. [62] studied the liquid jet atomization from elliptical nozzles by varying the aspect ratios and observed the phenomenon of axis–switching, i.e. the spray width was larger in the minor axis plane, then further downstream it became circular and eventually reversed its configuration along the jet axis. Crighton [63] also reported that elongated jets tend to exhibit lateral flapping motion along their minor axes. Even in case of air and gas jets, laboratory studies using elliptic nozzles [64, 65, 66] and nozzles with corners, e.g. rectangular, triangular, star-shaped [67, 68, 69] have observed that as the jet moves downstream, its cross section undergoes changes in its geometric shapes similar to those of the nozzle orifice but with axes successively rotated at angles characteristic of the jet geometry, denoted as the axis-switching phenomenon. This phenomenon is mainly responsible for the enhanced entrainment properties of noncircular jets, relative to comparable circular jets, and is a result of self-induced Biot-Savart deformation of vortex rings with non-uniform azimuthal curvature and interaction between azimuthal and streamwise vorticity. Due to Biot-Savart self-induction, portions of the vortex with small radius of curvature, such as the major axis section of elliptic rings or the vertices in square or triangular rings, will move downstream faster than the rest, leading to their deformation [45]. As a result, elliptical and rectangular jets have been reported to have greater entrainment rate than their equivalent circular jets [64, 70, and 71]. Axis switching results from faster growth rate of the jet’s shear layers in the minor axis plane (plane parallel to the elliptic minor axis) compared to those in the major axis plane. These differential growth rates result in a crossover point at a certain downstream distance from the nozzle where the jet’s dimensions at the two axes are equal. In general, the growth rate of the jet depends on many parameters, such as Reynolds number, initial
turbulence level and spectral content emanating from upstream disturbances, velocity and temperature ratio, nozzle geometry and aspect-ratio, and initial circumferential shear-layer thickness distribution [45].

The rectangular orifice presents a special case. It incorporates the features of aspect ratio, similar to an elliptical orifice and the effects of corners, similar to square and triangular orifices. Nozzle exit shape, aspect ratio, initial turbulence level, and Re affect the development of the jet. The spreading rate of the rectangular jet is typically higher at the wide section than at the narrow side. This results in axis switching similar to that of an elliptic jet. Hertzberg & Ho [72] found that the cross over location is directly proportional to the aspect ratio of the orifice. Similar to the Rayleigh’s analysis [5] for a cylindrical jet, Drazin and Reid [52] conducted stability analysis for planar jets. They found that an inviscid infinite plane jet is stable to all the disturbances because surface tension has always a damping effect and forces the surface back to its initial shape when perturbed as the minimum energy occurs when the two surfaces are parallel. However, a finite planar jet is always unstable to the surface tension instabilities in the form of surface ripples as the initial shape is not stable to any changes that bring the jet closer to the cylindrical shape. Thus, the basic tendency is towards contraction, which occurs with considerable inertial overshoot, leading to axis – switching phenomenon. Moreover, according to Soderberg and Alfredson [53], the jet is also subjected to the process of velocity profile relaxation as it is issued from the nozzle. The interaction of the relaxation of the boundary layer or turbulent eddies with the free surface tension and acceleration due to gravity generates potentially unstable waves which grow in amplitude downstream and contribute to the jet breakup. Konkachbaev et al.
observed inversion or axis switching phenomenon in slab jets and explained it a result of surface tension and corner vortices. They also observed standing surface capillary waves fanning out from the edges owing to turbulent velocity profile relaxation.

Because of the proposed better atomization and spray characteristics obtained from non-circular orifices, they have been used for practical applications as well. Kawamura et al. [55] studied the spray characteristics of a slit nozzle for direct injection gasoline engines in order to realize the concept of stratified charge combustion. The slit nozzle forms a thin fan shaped spray. The results were also compared with those obtained from a swirl nozzle. They employed slit nozzles of varying thickness and found out that the spray penetration increases with the slit thickness. However, varying slit thickness does not affect droplet size much. In comparison to the swirl nozzle, the slit nozzle gives better spray penetration, wider diffuse spray angle and finer atomization.

They determined some empirical relations for spray penetration and Sauter mean diameter of droplets based on their experimental observations.

For the first stage of penetration: \( t < t_c \)

\[
y = c_s \cdot \left( \frac{\Delta P}{\rho_f} \right) \cdot t^{0.25}
\]

For the second stage of penetration: \( t > t_c \)

\[
y = \left( \frac{4 \cdot c \cdot A_g \cdot \Delta P}{\rho_a \cdot \tan \theta \cdot \psi} \right)^{0.25} \cdot t^{0.5}
\]
where, y is the spray tip penetration,

c is the coefficient of discharge,

ρₐ is the surrounding gas density,

ρ₇ is the fuel density,

ρₒ is the air density under standard atmospheric conditions

t is the time after injection

tₖ is the critical time

Aₑ is the Inlet area of the slit orifice

θ is the half spray angle observed from the side

Ø is the spray angle observed from the front

Δ P is the difference between the injection pressure and the ambient gas pressure

cₛ is a constant.

Equation (2.14) is the same as obtained by Arai et al. [56] for the nozzle circular hole geometry at the initiation of injection. cₛ was determined to be 0.39 for diesel sprays based on experimental results. Similarly, the spray tip penetration after the first stage is determined by equation (2.16) based on Waguri et al.’s [57] spray momentum theory. The solution of equation (2.14) and (2.16) determines the critical time of penetration as given by equation (2.17).
Based on the theoretical analysis of the instability of the liquid film and neglecting the secondary breakup Dombrowski and Hooper [58] determined the relations for the Sauter mean diameter of the drops by the following equations.

For lower injection pressure,

\[ d_{32} \propto \Delta P^{-0.33} \cdot H^{0.33} \cdot \rho_a^{-0.17} \]  \hspace{1cm} (2.18)

For higher injection pressure,

\[ d_{32} \propto H^{0.5} \cdot \rho_a^{0.25} \]  \hspace{1cm} (2.19)

where, \( d_{32} \) is the Sauter Mean Diameter of the drop

\( H \) is the slit thickness.

Considering the propositions made by Dombrowski and Hooper [58] and Clark and Dombrowski [59] that the breakup length of liquid film decreases with increase in ambient air density which causes thicker liquid film and large initial drops at the breakup point and that droplet coalescence increases with surrounding gas pressure, Kawamura et al. [55] determined relations for SMD of droplets as follows.

For lower injection pressure \( \Delta P = 0.1 \) to \( 0.3 \) MPa,

\[ d_{32} \propto \Delta P^{-0.25} \cdot H^{0.3} \]  \hspace{1cm} (2.20)

For higher injection pressure \( \Delta P = 6 \) to \( 12 \) MPa,

\[ d_{32} \propto \Delta P^{-0.5} \cdot H^{0.1} \cdot \rho_a^{0.33} \]  \hspace{1cm} (2.21)

In order to achieve homogeneous lean air-fuel mixture for “rich and lean” combustion and “lean” diesel combustion, Yamamoto and Niimura [60], used a slit orifice nozzle. They expected to increase the spray surface area which facilitates greater air entrainment and a
more homogeneous mixture. They observed the spray from different directions, parallel to and perpendicular to the nozzle hole slit. When the fuel was injected in ambient pressure of 2 MPa, they found the spray geometry to be symmetrical about the spray axis and similar to that obtained from a conventional circular hole nozzle. Moreover, the spray penetration and volume of both the slit and circular nozzles were found to be nearly equal. The spray tip from the slit nozzle was found to be flatter which they attributed to droplet coalescence. Thus, they did not observe any improvement in air entrainment by changing the orifice geometry from circular to rectangular because of the large surface area of the jet in the latter case.

Studies on gases ejected from the noncircular nozzles with corners i.e., square and triangular showed that the presence of sharp corners in the orifice geometry can increase significantly the fine-scale turbulence at the corners relative to the flat segments of the orifice [73, 74] and enhance mass entrainment [75]. Shear-layer growth rates are different at the flat and vertex sections in square and triangular jets. This difference in spreading rate may lead to axis switching, or rotation of the jet geometry in the downstream direction. Stretching of the bent vortex by the shear stresses produces small-scale streamwise vortices at the corners. This process occurs only in nozzles with corners and is responsible for the initial axis switching and amplification of small-scale turbulence at the vertices [45].

Results of experiments, stability analysis, and simulations support the concept that the basic mechanism for the first axis rotation of the jet cross-section is the self-deformation of the vortex rings due to non uniform azimuthal curvature at the initial jet shear layer. However, subsequent axis rotations of the jet cross-section are not necessarily linked to successive vortex-ring axis rotations [45].
Many practical applications like fuel combustion, inkjet printers, medical applications, etc. require smaller droplet generation. However, it has been found that for a given fluid the injection pressure scales like $\gamma/r$, where $\gamma$ is the liquid surface tension and $r$ is the droplet radius. Thus, ejecting smaller droplets requires higher pressures. Chen and Brenner [76] have theoretically optimized the orifice geometry required to generate minimum droplet size and determined it to be a non–circular orifice in the shape of stretched triangles. Using numerical surface minimization techniques, McGuinness, Drenckhan and Weaire [77] have shown that further improvement can be achieved by making the boundaries of the triangular orifice three–dimensional or non planar.

**Summary**

Based upon these reviews, it can be concluded that the non–circular orifices induce enhanced instabilities in the jets and the sprays. Generally, a cylindrical jet emanated in ambient conditions is subjected to forces like surface tension, viscosity, inertia, gravitational and effects of turbulence, cavitation and aerodynamic forces. In case of non-circular geometric jets, the breakup phenomenon is different. Many of the research works done on the elliptical orifices have clearly shown that they undergo axis–switching phenomenon which quickens the disintegration process of the jet/ spray. Thus, the non-circular jets are more unstable. Hence, it is expected that non-circular orifices should give better atomization as compared to circular jets. Similar works on slit orifices have shown that slit orifice yielded better air entrainment and mixing. In liquid jets, axis switching is a result of competitive interaction between surface tension and inertia forces. Studies carried out on air and gas jets have also revealed the existence of the axis switching phenomenon. However, in case of
gases, it is explained to be an outcome of vortex ring deformation by self–induction. Due to lateral flapping, the jet surface disintegrates quickly, generating smaller droplets. Also, due to periodic change in the orientation of the jet profile, it has a better interaction with the surrounding gas which results in enhanced air entrainment and mixing. Despite of such major changes and advantages over circular orifices, it is very difficult to find such works which have extensively studied other non–circular shapes like square and triangles and even rectangle and ellipse for liquid jet pressures varying up to 1000 bars.

Through this work, we have attempted to explore the scope of investigation in the areas of non–circular jets and sprays. For a thorough study, analyses have been carried out on a large range of pressures, starting from a few psi going up to 1000 bars. Jets and sprays have been analyzed from different orientations and for a number of macroscopic and microscopic spray properties. The results obtained have been compared to those obtained from the circular orifices. Based upon our findings, we have tried to improve our understanding of the basic physical processes involved in jet breakup and atomization. For the better utilization of the depleting fossil resources and controlling the all–pervasive pollution, better advancements in the field of fuel atomization and spray combustion are required and we have tried to make a positive contribution in that direction.
CHAPTER 3: EXPERIMENTAL SETUP AND PROCEDURE

Low Pressure System

The low pressure water injection system consisted of a stainless steel water storage tank which was kept under pressurized conditions to supply high pressure water to the orifice. Tank pressure was controlled using regulated compressed nitrogen supply. Nitrogen gas was used to prevent rusting. High pressure seamless stainless steel tubes were used to transport water from the tank to the orifice inlet. A water filter was installed to the outlet of the supply tank to filter out any contaminants. The water flow to the orifice was controlled using a flow control valve along with a digital pressure gauge to monitor the injection pressure and pressure drops occurring in the supply system, especially in the filter. The orifice plate was installed in the orifice assembly. The orifice assembly (Figure 3-1) comprised of a cylindrical smoothening chamber of diameter 5 mm and about 32 mm long which delivered water to the orifice plate. The orifice plates were fabricated using stainless steel and the circular and non-circular orifices were machined using wire-cut electro discharge machining (EDM) process. The geometrical details of the orifices are provided in Table 3-1. Details of the experimental setup are shown in Figure 3-2.
Figure 3-1. Details of the orifice assembly.
Figure 3-2. Low Pressure Water Injection System.
Table 3-1. Geometrical details of the orifices (in m)

<table>
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<th>Circle</th>
<th>Dia 1: 0.000304</th>
<th>Dia 2: 0.0002870</th>
<th>Avg. Dia: 0.0002955</th>
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<td>Length 1: 0.000561</td>
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<td>Length 2: 0.000564</td>
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<td>Side 4: 0.0002617</td>
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<tr>
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<td>Side 2: 0.000381</td>
<td>Side 3: 0.000375</td>
<td>-</td>
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</tbody>
</table>

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<th>% Diff. in area</th>
<th>D_h (in m)</th>
<th>L/D ratio</th>
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<td>5.82578 x 10^{-8}</td>
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<td>0.0002113</td>
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</table>

Figure 3-3a –d shows the high – resolution image of the different orifices used in the present study. The injection pressure (gauge) was varied from 0 psi to 1000 psi. 0 psi corresponds to no external pressure and the liquid was allowed to fall freely under the effect of gravity and hydrostatic pressure of the water column. High speed visualization techniques were employed to capture the flow behavior. A high speed camera (Phantom 4.3) with a Nikon® 50-mm f/1.8 lens was used. The pixel resolution was varied as per the requirement in order to capture the details of the breakup and axis-switching phenomena. A front lighting system was used to illuminate the jet. For this purpose, a 1000 Watt lamp and a white screen reflector were employed. In order to observe the geometrical development of the jets from the non - circular orifices, the jets were analyzed from different orientations or view planes, including those containing the straight edges and those containing the sharp corners or vertices. Both the nitrogen gas supply pressure and the water injection pressure were noted.
No appreciable differences in the two pressures were noted, hence, negligible pressure drop occurred in the supply system. Also, it means that the hydrostatic pressure of the water column was also negligible and hence, has not been included in the measurements.

Figure 3-3a Circular orifice. Dia: 295μm

Figure 3-3b Rectangular orifice. 562μm x 133μm
Figure 3-3c Square orifice. Side: 263μm x 263μm

Figure 3-3d Triangular orifice. Side: 347μm x 375μm x 381μm.

The experiments were conducted for a wide range of flow conditions of the discharging liquid jets. Different parameters characterizing the flow conditions are provided in the following tables.
Table 3-2 Physical properties

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<td>Surface Tension in N/m</td>
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<td>Density of Air in kg/m³</td>
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Table 3-3 Reynolds Number for different flow conditions

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Table 3-4 Liquid Weber Number for different flow conditions

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<td>5,998.30</td>
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Table 3-5 Gas Weber Number for different flow conditions

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<td>8.62</td>
<td>16.92</td>
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<td>31.56</td>
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The different flow parameters have been calculated using the hydraulic diameter of each orifice and the steady mass flow rate measurements. The steady state mass flow rates were measured using a precise spring balance and stopwatch. The discharged liquid was allowed to attain its steady state and then collected in a vessel. Based upon the pre-injection and post-injection masses of the vessel and the time duration recorded in the stopwatch, mass flow rates were calculated using the following relation

\[ \text{Mass flow rate}, \dot{m} = \frac{m_f - m_i}{\Delta t} \]  

(3.1)

where, \( m_f \) is the post-injection mass of the collecting vessel,

\( m_i \) is the pre-injection mass of the collecting vessel,

\( \Delta t \) is the time recorded on the stopwatch.

Mass flow rate was measured five times for each injection pressure and an average was then calculated. Using the mass flow rate values, volumetric flow rates and then exit jet velocities
were calculated. Based on the exit velocities obtained, coefficients of discharge (CD) were calculated for each injection pressure and all values obtained were less than 1.

For each injection pressure, water was injected 10 times. The cine files obtained from the high speed camera were then processed to obtain the images. Calculations were carried out on these images and parameters, like breakup length, droplet size and jet width, were calculated for each of the 1000 images. Final values have been obtained by taking an average of the 1000 measurements.

High Pressure System

Common rail high pressure injection system

The injection system is illustrated schematically in Figure 3-4. A first generation common rail fuel system is built to control and maintain the fuel at a given constant injection pressure (up to 1350 bar). The fuel stored in a fuel tank is delivered by a low pressure pump and passes through a fuel filter (Caterpillar 1R-0751). The filtration media inside the filter is able to remove 98 percent of any particles larger than 2 \( \mu m \) in the fuel. The filtered fuel is transported to the high pressure pump (BOSCH CR/CP1S3/R70/10-16S) which is driven by a 3 phase, 2 horsepower AC motor (GE K1496, maximum speed: 1725 rpm) with timing belt and pulleys. An idler pulley was provided to enhance the tension of the belt. The common rail (BOSCH 0-445-214-122) has a pressure sensor (BOSCH 07-05-08-03135) providing the pressure values inside the common rail. Specially fabricated nozzles with circular and non-circular orifices are used in this work. Details of the nozzle dimensions are given in Table 3-6 and Figures 3-5 to 3-8. The orifices were drilled by the EDM fabrication process. The vibration caused by operating the AC motor and high pressure pump shook the equipment.
while conducting experiment, therefore, a ‘V’ – shaped holder is used to fasten the nozzle to curb its vibrations during the experiment.

![Figure 3-4. Schematic representation of the high pressure common rail fuel injection system](image)

**Table 3-6 Geometrical details of the orifices (in m)**

<table>
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<tr>
<th>Dimensions</th>
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<th></th>
<th>X-sec\textsuperscript{na}l Area (m\textsuperscript{2})</th>
<th>% Diff. in area</th>
<th>Depth (in mm)</th>
<th>L/D ratio</th>
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<td>-</td>
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<td>Side 2: 0.000146</td>
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<td>2.08 x 10\textsuperscript{-8}</td>
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<td>1.21 x 10\textsuperscript{-8}</td>
<td>-43.7</td>
<td>0.7</td>
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</table>
Figure 3-5. Details of the circular orifice. Dia.: 0.165mm

Figure 3-6. Details of the circular orifice. Sides: 0.205 x 0.146 mm.

Figure 3-7. Details of the circular orifice. Sides: 0.142 x 0.146 mm.
Injection pressure control system

The fuel pressure in the rail is controlled by a DAQ (NI 195509D-01L) with a PID loop program built in LabVIEW 2010. The PID loop control software interface and block diagram are illustrated in Figure 3-9.

---

Figure 3-8 Details of the circular orifice. Sides: 0.171 x 0.161 x 0.169 mm.

Figure 3-9. LabVIEW PID loop interface and block diagram.
The DAQ acquires the pressure signal from the pressure sensor of common rail and compared the data with desired pressure set by the operator. When the fuel pressure inside common rail is not consistent with the set pressure, the PID controller changes the driving output voltage to the pressure regulator circuit, which is shown in Figure 3-10, to control the opening and closing of the pressure regulator solenoid valve and to adjust the amount of fuel returned from the high pressure pump to the low pressure fuel lines.

![Pressure regulator circuit](image)

**Figure 3- 10 Pressure regulator circuit.**

This way, the pressure in the rail can be maintained at the pre-set levels. The activation of injection is controlled by a pulse/delay generator (Stanford research system, Inc.), by which we were able to control the length of injection signal (injection duration) and output a single shot signal to the injector driver circuit details of which are given in Figure 3-11a & b. The injector driver circuit then controls the opening and closing of the injector valve. Safety equipment, a 3 amp fuse was placed between the power supply and inlet voltage of injector driver circuit to prevent overloading of the circuit components.
Figure 3-11 (a) Injector driver circuit.

Figure 3-11 (b) Injector driver circuit diagram.
Particle size measurement system

The particle size of fuel spray was measured by a LDPA (laser diffraction particle analyzer) by Malvern Instruments (SprayTec, MAL 1009475). In laser diffraction particle size analysis, an ensemble of particles passes through a broadened beam of laser light which scatters the incident light onto a Fourier lens. This lens focuses the scattered light onto a detector array. By using an inversion algorithm, a particle size distribution is inferred from the collected diffracted light data. Sizing particles with this technique ensures full characteristics of the sample depending on accurate, reproducible and high resolution light scatter measurements. Spraytec software was used to take and process the data. The data acquisition rate was set to be 10 kHz and 300 mm lens was chosen for the size range (0.1 \(\mu\text{m}\) - 900 \(\mu\text{m}\)). The measurement trigger was connected to the same pulse generator as the injector driver to make sure these two devices were synchronously triggered. The measurement duration was 5 ms after the trigger which covered the whole process of spray formation and atomization. The detector range was selected 20 - 30 of 36 laser beams to eliminate false signals and avoid erroneous results as illustrated in Figure 3-12.

![Figure 3-12 Examples of detected signals.](image-url)
The LDPA instrument was located at different positions in axial directions downstream of the spray to study the droplet size distribution inside the spray structure. The compared results will be discussed in later chapters. For each test case, 10 runs were made and droplet sizes were measured. Finally, an average of all the 10 runs was taken to determine the droplet size at different locations. For a better understanding, the sprays from the non-circular orifices were analyzed from different orientations, similar to the low pressure analysis.

**Spray image acquisition system**

A high speed camera (Phantom 4.3) with a Nikon® 105-mm f/1.8 lens was used to capture the images of the fuel spray. It provided a frame rate of 7312 frames per second at a resolution of 112 x 600 with the exposure time of 11 µs in this study. A 1000 Watt spot light was used as the light source for the image acquisition. The measurement trigger is also synchronous with the injector trigger. After an averaged injection delay of 0.5 ms, the spray images were acquired up to 6 ms which is also the injection appearance duration time. For each test condition, five runs were made each comprising of 50 frames. Based on these 250 frames, spray properties like tip penetration, velocity and acceleration, spray width, cone angle and volume were calculated and then an average value was evaluated. Properties were evaluated for different orientations for determining the complete 3-dimensional geometry of the non-circular sprays. Thus, the fuel was injected in the vertical direction as it gave the flexibility of location the camera in different locations and capturing images from different orientations/ view planes. The camera was mounted on a rail which was pinned near the injector so that the whole setup can be moved around the injector and images be captured from different orientations.
Figure 3-13 Experimental setup for the high speed image acquisition system
Table 3-7 Details of the operating conditions

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<th><strong>SprayTec, MAL 1009475</strong></th>
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<td>Detect size range</td>
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<tr>
<td>Detector range</td>
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**Spray image acquisition system**

<table>
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<tr>
<td>Resolution</td>
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</tr>
<tr>
<td>Exposure time</td>
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CHAPTER 4: RESULTS AND DISCUSSION

Low Pressure Analysis

As discussed earlier, jet breakup and spray characteristics depend on the fluid flow conditions which can be well represented in the form of non dimensional numbers Re, We and Oh [78, 21]. The breakup process is defined for the parameter $\sqrt{We_L}$ as it provides the linear dependence of the process on jet velocity and at the same time retains the qualitative aspects of the flow.

Steady State Mass Flow Rate Measurements

The steady state mass flow rates form different orifices for pressures varying from 0 psi to 1000 psi are presented.

![Steady State Mass Flow Rate Diagram](image)

Figure 4-1 Variation of the steady state mass flow rate for the low pressure jets under different flow conditions.
As it can be seen, the mass flow rates are nearly the same for lower injection pressures, however, for pressures above 200 psi, rectangular orifice with slightly higher area discharges higher mass flow rate as compared to the other cases.

Based upon the mass flow rate measurements obtained as shown above, the volumetric flow rate was calculated and thus, the jet exit velocity was obtained using the relation.

\[
\text{Vol. Flow Rate}, \dot{V} = A_e \times V_e
\]  

\begin{equation}
(4-1)
\end{equation}

where, \(A_e\) is the Area of the orifice and \(V_e\) is the Jet exit velocity.

![Figure 4-2 Variation of the exit velocity for the low pressure jets under different flow conditions.](image)

As the triangular orifice has slightly smaller area, as a result, the jet exit velocity is slightly higher than the other cases. The same jet exit velocity is used for calculating the non-
dimensional numbers Re and We for characterizing the flow conditions at different injection pressures.

**Reynolds Number Calculation**

Reynolds number is a dimensionless parameter that gives the ratio of the inertial forces of the jet flow to the viscous forces of the fluid. It can be calculated using the following relation:

$$Reynolds\ number, \ Re = \frac{\rho_f V_e D_h}{\mu}$$  \hspace{1cm} (4.2)

where, $\rho_f$ is the jet fluid density,

$V_e$ is the jet exit velocity,

$D_h$ is the hydraulic diameter of the orifice

$\mu$ is the dynamic viscosity of the fluid.

The hydraulic diameter of non-circular orifices can be calculated using the following relation:

$$Hydraulic\ diameter, \ D_h = \frac{4 \times Ar.}{P}$$  \hspace{1cm} (4.3)

where, Ar. is the orifice cross sectional area,

P is the perimeter of the non-circular geometry.

The variation of the Reynolds number for the flow from different orifices at varying pressure conditions is presented. It can be noted that the flow behavior is similar for the circular, square and triangular shaped orifices at lower injection pressures. However, at higher pressures, the level of turbulence is highest in the circular orifice followed by the square and then the triangle. Turbulence is the lowest in the flow from rectangular orifice.
In fact, it is interesting to note that in case of rectangular orifice the flow remains laminar even at 15 psi while for the other cases, it has already entered the transition zone at 10 psi. Moreover, flow from the square orifice is the first to show turbulence as can be seen in the figure below.
Weber Number

The most important parameter in characterizing the jet breakup is the Weber’s number as it gives the ratio between the fluid inertia and the surface tension forces. It can be obtained using the following relation:

\[
Weber\ Number, \ We = \frac{\rho_f V_e^2 D_h}{\sigma}
\]  

(4.4)

where, \(\rho_f\) is the density of the fluid,

\(V_e\) is the jet fluid exit velocity,

\(D_h\) is the hydraulic diameter of the orifice shape,

\(\sigma\) is the fluid surface tension.

With the variation in jet exit velocity, the Weber number for the jet liquid as well as the ambient gas changes. As mentioned earlier, it is value of Weber number only based on which
the different jet breakup regime criteria are defined. The variation in $\text{We}_L$ and $\text{We}_G$ are shown below for the different orifices.

Figure 4-5 Variation of the $\text{We}_L$ for the low pressure jets under different flow conditions.

Figure 4-6 Variation of the $\text{We}_G$ for the low pressure jets under different flow conditions.
Thus, the Weber number for both the jet liquid as well as the ambient gas has increased linearly with the jet exit velocity. Owing to difference in their measurements, the Weber number for each orifice is different even though the injection pressures are same. However, the values are in a close range. Important to note is that, even at pressure as high as 1000 psi, the gas Weber number, We_G, for the triangular case only has crossed the value of 40.3, which is the mark of onset of the atomization regime [27]. Thus, the jets obtained from all other cases have undergone breakup up to second breakup regime only.

**Development of Flow with Increase in Injection Pressure**

Image sequences have been provided to present the breakup behavior of liquid jets for different injection pressures or $\sqrt{We_L}$ conditions. The viewing area is confined to the immediate vicinity of the breakup location. Since the breakup length is different for each orifice, in order to capture the jet breakup phenomenon, it was required to set up the high speed camera at different locations and at different resolutions. Thus, the images displayed are not up to the same scale. However, while measuring the length proper scale factor was used corresponding to the resolution used. As has already been mentioned, for different orifices the Weber numbers and thus, the flow conditions differ even if the injection pressure is same.

**Circular Orifice**

The breakup length for the circular orifice was found out to be very long as compared to the other cases. Owing to the limitation of the high speed camera’s field of view, it was not possible at some pressures to capture the entire breakup process of the circular orifice in one
shot. Hence, the photographs of the jet were taken at different axial locations and at different instants. However, they have been patched up together with no spatial discontinuity.

Figure 4-7 Evolution of the low pressure circular jets under different flow conditions. Black bars locate instantaneous breakup points. The relative location of the black bars gives a sense of trend of the changes in the breakup lengths with increase in injection pressure. Numbers below the images indicate the injection pressure in psi.
The breakup of the circular liquid jet is axisymmetric at low $\sqrt{We_L}$ in nature as predicted by Rayleigh [35]. As can be seen from Table 3-4, $We_L$ for the circular orifice is well above the value of 8 which is the required minimum for the formation of a jet. Also the corresponding $We_L$ value is below 0.4 for pressures up to 10 psi. Thus, till 10 psi the circular jet is under Rayleigh breakup regime. It can be seen from the figures that the droplet formation occurs several jet diameters away from the orifice and the drop size is nearly the same as the jet diameter. Moreover, drops are pinched off from the end of the jet. As the $We_L$ number further increases with increase in injection pressure, the jet breaks up into ligaments in place of drops. These ligaments after travelling downwards further break up into drops under the effect of aerodynamic forces. This is the same behavior as observed by Grant and Middleman [20]. Further increase in $We_L$ leads to the development of sinuous waves on the jet surface. These waves are clearly visible on the jet injected at 200 psi. As per the criteria mentioned earlier, the circular jet is in first – wind induced regime for pressures up to 250 psi and is in the second wind induced regime for pressures 500 to 1000 psi. This is clearly visible from the images of 500, 750 and 1000 psi. Several jet diameters downstream the jet surface starts stripping off and the break up does not occur on the entire cross section. Moreover, the droplets formed are much smaller than the jet diameter. Since, the jet intact-surface length has not reduced to zero even at 1000 psi, the jet has not entered the atomization regime. The trend of the breakup curve can be seen from the bars drawn on the images at the corresponding breakup locations. As expected, the breakup length increases during the first wind induced regime, reaches its peak and with the onset of second wind induced regime it starts decreasing.
Rectangular Orifice

Figure 4-8 Evolution of the low pressure rectangular jets under different flow conditions.

First image in each pair belongs to the view ‘RL’ while the second one to the view ‘RS’. The resolutions of the images are different. Numbers indicate the injection pressure in psi. The locations in ‘RL’ view where crests are present, at the same location in ‘RS’ view necks are present. This is due to the ‘axis-switching’ phenomenon.
Figure 4-9 Evolution of the low pressure rectangular jets under different flow conditions. Rest details are same as Figure 4-8.
The development of the flow behavior from the rectangular orifice is depicted pictorially. The images are presented in pairs. For each pair, the images were taken from two different orientations by placing the high speed camera in two orthogonal planes, viewing the longer side (now referred to as view ‘RL’) and the shorter side (now referred to as view ‘RS’). The first image in each pair corresponds to the one taken viewing the longer side, i.e. view ‘RL’. The resolutions of the images for the two orientations are different for all the pressures. As a result, the scale is different for the images in each pair. This is the reason that the jet in the second images in each pair looks smaller and thinner. For 0 psi, the jet emanated from the rectangular orifice is similar to the circular orifice and breaks up nearly axisymmetrically. The jet is completely different from the circular jet at 5 psi. Thus, for flow with Weber numbers between 19.47 (corresponding to 0 psi) and 112.79 (corresponding to 5 psi) the rectangular jet behaves similar to the circular jet. This is because the surface tension forces are very dominant in this regime and seek minimum surface area, thereby suppressing any effect of the asymmetric orifice. Thus, the jet transforms into a cylindrical jet after coming out from the rectangular orifice. This behavior is similar to that observed by Kasyap et al [43, 44] from the elliptical orifice. The breakup of the jet in this regime is the same as Rayleigh regime. The drops formed are much bigger than the hydraulic diameter and are formed by pinching off from the jet’s end. For 5 psi, the jet acquires an entirely different shape. In view ‘RL’, the jet comes out of the orifice with a width corresponding to the length of the longer side of the orifice. As it moves downstream the jet width decreases and a “neck” is formed. Further downstream, the jet width again increases and forms a crest. This behavior is repeated periodically along the jet length. The behavior of the jet width in view ‘RS’ is
entirely opposite. The jet width at the orifice exit corresponds to the length of the shorter side of the orifice. The appearance is similar to the “neck” observed in the image of view ‘RL’. As the jet travels downstream, the jet width increases and forms a crest and the trend continues along the jet length. Thus, the jet periodically varies its width in the two planes. Thus, it can be concluded that at certain points along the jet length the jet widths in the two planes will be equal, i.e., the jet becomes nearly circular. This behavior is same as what has been defined as the axis-switching phenomenon. Thus, the asymmetric geometry of the orifice resulted in axis – switching phenomenon as has been observed in elliptical orifices [43, 44, 64, 65, 66]. The axis – switching occurs multiple times because of the interaction between surface tension and inertia forces [43]. Due to axis – switching the jet surface appears to be in the form of a spatial wave. For such a wave, the wavelength can be described as the distance between two necks or two crests. With increase in $We_L$, the surface of the jet gets ruffled. Though the axis switching phenomenon is still visible, the jet surface has been greatly deformed by some new disturbances. These disturbances arise because of other factors including turbulence, aerodynamic forces, etc. [43, 44]. From table 3-3 and 3-5, the values of the Re and $We_G$ can be noted. The jet remains laminar till 15 psi and $We_G$ for 10 psi is 0.25 which is very close to 0.4. As mentioned by Miesse [27], Pan and Suga [84] and Reitz [21], the effect of ambient gas becomes visible at $We_G$ nearly equal to 0.4. Thus, aerodynamic forces seem to be responsible for the development of surface ruffles which start to originate from 10 psi. It can be noted that the wavelength of the axis switching phenomenon increases with increase in injection pressure or jet Weber number. It has been observed by Rayleigh [5] and Geer and Strikwerda [79] that the wavelength varies linearly
with the Weber number. In the image for 250 psi, one crest can be seen in view ‘RL’ just after which the jet gets disrupted. For pressures above 250 psi, it can be seen that the crest is formed right after the orifice exit but the wavelength of the crest is greater than the breakup length of the jet and hence, the jet disrupts before the jet converges to form a neck. Furthermore, in the images of view ‘RS’ for pressures 200 and 250 psi, development of some transverse waves can be seen. Depending on the wavelength of the axis – switching process and the location of the transverse waves, the jet width should be higher in ‘RL’ view. Thus, the jet behaves like a thin sheet whose plane is perpendicular to the ‘RS’ view plane. Thus, the liquid sheet develops transverse waves similar to those developed on planar liquid sheets [44]. These waves are present only in ‘RS’ plane and seem to originate at 200 psi and by 250 psi become so violent that they cause the jet to break up.

With regards to the droplet formation, it can be noted from the images that up to 10 psi the droplets formed are nearly the same size as the hydraulic diameter. For higher pressures, the jet breakup results in the formation of ligaments. Possibly, the necks formed due to axis switching tend to act like weak points which are susceptible to the growing disturbances and the portion of the jet beyond the neck breaks off as a ligament. Moreover, the jet produced from rectangular orifice is more of a liquid sheet than a jet. Hence, the droplets formed are expected to be in the form of ligaments which may further breakup into large irregular drops. It should also be noted that here, in case of rectangular orifice, the jet have undergone breakup within one frame only and no need of taking shots at different axial locations arose. Though actual measurements depend upon the resolution and the scale factor, it still gives a
sense of shorter breakup length for the rectangular orifice. However, actual comparison will be based on measured length only.

**Square Orifice**

The development of the flow from the square orifice is presented for varying injection pressures. Images are provided in groups of three. Each group corresponds to different pressure. However, the images have been taken from three different planes of view. The first two images were taken viewing two different sides of the square orifice at right angles and from now on will be referred to as view ‘SF’ and view ‘SS’, respectively. The third images were taken from the plane of view in line with one of the diagonals of the square orifice, thus, looking at one of its vertices. This will be referred to as view, ‘SV’. Once again, significant differences can be observed both from the circular jet as well as the rectangular jet. However, since the square orifice and so does the triangular orifice lack aspect ratio effects in their geometry, their jets are expected to be somewhat similar to the circular orifice. Whatever changes that are presented can, thus, be attributed to the presence of sharp corners in square and triangular geometry. Being non-circular geometries, both square and triangular jets are also expected to demonstrate the axis–switching phenomenon. It is difficult to determine the existence of axis switching phenomenon just by visual inspection. Axis switching is prominently visible in elliptical and rectangular orifices because of the differences in their widths in the major and minor axes planes. However, this is not the case for square and triangular orifices as depicted in the figure below.
Since the differences in the widths in the different view planes is zero or very small, therefore, it is very difficult to determine the presence of axis switching visually.

At 0 psi, the jet under the effect of strong surface tension forces the jet appears to come out as a thin cylindrical jet, i.e., the effect of the presence of asymmetric geometry has been suppressed. Thus, the jet is similar to a cylindrical jet and undergoes breakup through Rayleigh mechanism. With increase in Weber number, the smooth jet surface is lost and various perturbations arise on the jet surface. As can be seen from Table 3-3 and has been shown on Figure 4-3, the jet from the square orifice is the first to show turbulence at 25 psi while circular and triangular jets show turbulence at 35 psi. But even for pressures below 25 psi, i.e., 10 and 15 psi, the surface of the square jet appears more ruffled. From table 3-5, it can be seen that the rate of increase in $W_{e_G}$ with change in injection pressure is high for the square jet as compared to the circular orifice. The jet enters first – wind induced regime ($W_{e_G} > 0.4$) at 10 psi only while the circular jet has entered it at 15 psi. Thus, it can be
concluded that a factor is present which is inducing turbulence at a quicker rate and augmenting the effect of ambient gas at a higher rate in the square jets as compared to the circular jets. Since the only difference in the square and circular geometries is the presence of sharp corners, these aggravated perturbations on the surface of square jets can be attributed to them. Since the sharp corners are present in triangular orifices also similar behavior is expected from triangular jets. In fact, the angularity in triangular orifice is acute (in square orifice the corners have right angles), the small radii of curvature of triangular orifice should induce perturbations more severe than the square orifice. This will be discussed in the section on triangular jets.

Regarding the breakup of the square jet, it can be seen that with increase in $W_{el}$ the breakup length of the jets are increasing. Moreover, the droplets are pinching off from the jet and are of nearly the same size as the hydraulic diameter. Thus, the jet behavior corresponds to the first induced regime. At higher injection pressures, square jets also tend to breakup in the form of ligaments. Transverse waves can also be observed far away from the orifice for injection pressures of 500 psi and above. In rectangular jets, these waves have appeared at a comparatively lower pressure of 200 psi. The presence of such transverse waves indicates the sheet like behavior of the square jet similar to rectangular jets. Based on the $W_{ec}$ value from Table 3-5, it can be seen that the square jets enter the second wind induced regime at 500 psi ($W_{ec} > 13$) just like jets from other orifices. As per the second wind induced regime, the jets for 500 psi and higher injection pressures, the jet surface has began to strip off but still this process is not prominently visible at 500 psi. The droplets generated from surface
disruption are much smaller than the hydraulic diameter. Additionally, a considerable increase in jet width can be observed for injection pressures from 250 to 1000 psi. This is because of the turbulence and increasing effect of the aerodynamic forces.
Figure 4-11 Evolution of the low pressure square jets under different flow conditions. Images are in groups of 3. The first image belongs to the ‘SF’ view, the second image belongs to the ‘SS’ view and the last image belongs to the ‘SV’ view. Numbers indicate the injection pressures in psi.
Figure 4-12 Evolution of the low pressure square jets under different flow conditions. Rest details are the same as Figure 4-11.
Figure 4.13. Evolution of the low pressure square jets under different flow conditions. Rest details are the same as Figure 4.11.
Triangular Orifice

In the case of triangular orifice, the images were taken from two different planes of view. One looking at one of the sides of the triangular orifice, which will be referred to as view ‘TS’ and the other looking at one of the vertices, which will be called, view ‘TV’. Thus, for each injection pressure, a pair of images is shown in figure 4-14. The behavior of the triangular jet at 0 psi is similar to the circular jet. Owing to the strong surface tension forces at this $We_L$, the effects of the triangular geometry have been suppressed. The jet breaks up as per the Rayleigh regime. As the $We_L$ increases, the effects of the presence of sharp corners become evident. Surface perturbations arise with increase in injection pressure. As per the Table 3-3 and 3-5 even at low injection pressure of 10 psi, the jet is no more laminar and is undergoing transition to turbulence. Also, the $We_c$ value has crossed the limiting value of 0.4 and thus, has entered the first – wind induced regime. Such strong interaction with the ambient gas even in the absence of turbulence can be attributed to the sharp corners. As expected and mentioned earlier, due to the presence of acute angles in the orifice geometry the interaction of the triangular jet is stronger than the square jet. The droplets formed in the first induced regime are comparable with the hydraulic diameter. With increase in $We_L$, ligaments break off from the jet which undergo further breakdown. The $We_c$ value is 8.62 at the injection pressure of 250 psi as compared to other jets. The triangular jet is about to enter the second – wind induced regime. This is evident from the jet appearance as well. The jet surface is very close to disruption at 250 psi. At injection pressures of 500 psi and above, the jet is in the second – wind induced regime and its surface can be seen to strip off and the resultant droplets produced are very small as compared to the jet diameter. In fact, at
injection pressures of 1000 psi, the intact surface length of the jet has nearly reduced to zero. This indicates that the jet is about to enter in the atomization regime. This is also evident from the $W e_G$ value in table 3-5 which is 31.56 and is approaching the value of 40.3 which is the minimum $W e_G$ required for atomization [27]. Similar to the square jets, no appreciable axis – switching phenomenon is visible in triangular jets.
Figure 4-14 Evolution of the low pressure triangular jets under different flow conditions. Images are in pairs. The first image belongs to the ‘TS’ view and the second image belongs to the ‘TV’ view. Numbers indicate the injection pressures in psi.
Figure 4-15 Evolution of the low pressure triangular jets under different flow conditions. Rest details are the same as in Figure 4-14.
Comparison of the Breakup Behavior

The cine files recorded using the high speed camera have been processed using the Image Processing Toolbox of MATLAB. Each frame of the cine files has been converted into an image. These images were then subjected to edge detection using sobel edge detection algorithm after required cropping and contrast adjustment. The binary images, thus, obtained were used for the measurement of the jet breakup length. The image was analyzed along its length and the first location of jet detachment was marked and the jet breakup length was measured. The procedure is displayed in the images given in Figure 4-16.

![Figure 4-16 Demonstration of the procedure of jet breakup length $L_b$ measurement using MATLAB. (a) Circle, (b) RL, (c) SF, (d) TS jets at 10 psi injection pressure.](image-url)
For each injection pressure, 5 shots of the steady state liquid jets were taken. Each shot comprised of 1000 frames. Thus, for each flow condition 5000 different images of jet breakup phenomenon have been evaluated. Figure 4-16 depicting the variation of the breakup length for different jets at varying flow conditions has been prepared using the average value of the 5000 images for each injection pressure. Similarly, for all other parameters like jet width and droplet size an average of 5000 different values is calculated corresponding to each flow condition. As mentioned, the values in the chart represent the average values and should not be compared with the instantaneous lengths depicted in the images of the jets provided in the previous section. Jet breakup is a dynamic phenomenon. Even for given flow conditions, it is a result of continuous interaction between a number of forces including the inertia, surface tension, viscosity and aerodynamic, turbulence and cavitation effects. As a result, the jet breakup length varies continually with time along the jet axis. However, this temporal variation is different from the one induced due to change in flow conditions. Thus, once again, the time averaged breakup length should not be confused with the instantaneous breakup lengths. Owing to the differences in the geometries, the measurements of the breakup length, $L_b$ have been non-dimensionalized / normalized by dividing them with the corresponding hydraulic diameters of their orifices. The $L_b$ values have been plotted against the $\sqrt{We_L}$ values as it is a non – dimensional parameter giving linear dependence of the breakup length with the jet injection velocity. Though the $We_L$ value is different for the different orifices at different injection pressures but still the values are in close range with each other.
The chart has been plotted for injection pressures up to 250 psi. For the remaining higher injection pressure, it was difficult to accurately measure the breakup length. This is because all the jets enter the second wind induced regime at injection pressures above 250 psi. Thus, the number of droplets is very large which makes the clear identification of breakup location difficult.

The chart clearly demonstrates the difference in the breakup length obtained from circular and non-circular orifices. The breakup lengths for all the orifices have increases nearly linearly as expected from the Rayleigh and first wind induced regimes. Interestingly, the normalized breakup lengths from the non-circular orifices tend to coincide with each other and the maximum value obtained at 250 psi is only 30% of the normalized breakup length.
from circular orifice under identical flow conditions. This emphasizes on the fact that asymmetric geometry induces enhanced unstable growths to the liquid jet as compared to the circular orifice. Thus, the instabilities experienced by non–circular jets are different from those experienced by circular jets. The same behavior was observed by Kasyap et al and Amini and Dolatabadi [43, 44 and 51] in case of elliptical orifices.

![Graph showing the variation of the non-dimensionalized breakup length at low $\sqrt{We}$ conditions. Error bars are not included.](image)

However, for flow conditions corresponding to 35 psi, the normalized break up lengths obtained from all the orifices appear to be the same. This has been highlighted on the chart. A closer look at the chart under these conditions reveals that except the rectangular orifice, breakup lengths from all other orifices tend to follow the same trend. Similar behavior was
observed from the visual inspection of the images where at low $We_L$ conditions the square and triangular jets tend to behave like a circular jet owing to the dominant surface tension forces. But the rectangular jets have followed a different trend due to the presence of axis switching phenomenon. Thus, the difference in the behavior of rectangular jets from other jets can be attributed to the axis switching phenomenon. After a certain threshold $We_L$ is achieved, even square and triangular jets tend to deviate from the circular jet behavior and the breakup lengths obtained from rectangular, square and triangular jets are nearly the same. This similarity points out that under these flow conditions all the non-circular jets are experiencing a common phenomenon. Rectangular, square and triangular orifices all are asymmetric and have sharp corners but the latter two lack the aspect ratio effects present in the rectangular shape. The axis switching phenomenon is prominently visible in rectangular and elliptical orifices due to the aspect ratio effect in their geometry. Since the square and triangular orifice lack this feature, it is quite possible that axis switching is present but not clearly visible. This needs further investigation of the jet behavior.

Jet Width Measurement

As per the definition of axis – switching, a jet emanated from a rectangular or an elliptical orifice, undergoes lateral flapping and its major and minor axes periodically change their orientation along the jet axes. During this lateral flapping the jet also assumes circular cross section. Thus, for a rectangular jet, if the width is greater in major axis plane, it will gradually reduce and the width in the minor axis plane will gradually increase. Eventually, the jet width in the major axis plane will become smaller than the jet width in the minor axis plane. During the complete change in the orientation, the jet widths in two planes will nearly
be the same and this is when the jet acquires a circular cross section. Based on this assumption, the jet width for the all the flow conditions was measured. For each flow condition, an average of jet width from 5000 different images has been calculated. The width measurement has been carried out only till the breakup location of the jets.

**Rectangular Jets**

The axis switching is not visible at 0 psi and the jet is said to be behaving like a circular jet. But the widths in the two view planes are completely different and increase linearly along the jet axis. Though the jet appeared cylindrical, actually the behavior is different. This is also depicted in the jet width behavior obtained at 0 psi Figure 4-19.

![Image](image.png)

*Figure 4-19 Variation of non-dimensionalized jet width in different view planes at 0 psi.*
Figure 4-20 Variation of non-dimensionalized jet width in different view planes at 15 psi.

Figure 4-21 Variation of non-dimensionalized jet width in different view planes at 50 psi.
Thus, the behavior of the jet widths in the two orientations is the same as what was expected. Hence, it can be seen that plotting the jet width along the jet axis can easily depict the phenomenon of axis switching. Similarly, the jet widths are plotted for the square and triangular orifice from different orientations.
Square Jets

Figure 4-23 Variation of non-dimensionalized jet width in different view planes at 0 psi. Error bars are not included.

Figure 4-24 Variation of non-dimensionalized jet width in different view planes at 5 psi. Error bars are not included.
Figure 4.25 Variation of non-dimensionalized jet width in different view planes at 15 psi. Error bars are not included.

Figure 4.26 Variation of non-dimensionalized jet width in different view planes at 35 psi. Error bars are not included.
For pressures up to 35 psi, the jet widths in the three view planes remain nearly constant along the jet axis with slight variations. Thus, the jet remains symmetric and behaves similar to the circular jet up for flow conditions up to 35 psi. Beyond 35 psi, variation in jet widths starts to vary along the jet axis. The variations increase with injection pressures. For example, at 50 psi, though the jet width remains nearly the same in the ‘SF’ view plane, the jet widths in the ‘SS’ plane is initially similar to the width in the ‘SV’ plane. Then, as the jet moves downstream the two widths differ. Further, downstream the width in the ‘SS’ plane is more than the ‘SV’ plane width. Eventually, all three widths become equal. Similar, phenomenon can be seen at higher injection pressures of 200 and 250 psi. Thus, it can be concluded that axis switching is not present for flow conditions corresponding to injection pressures of 35 psi and below.

Figure 4-27 Variation of non-dimensionalized jet width in different view planes at 50 psi. Error bars are not included.
Figure 4-28 Variation of non-dimensionalized jet width in different view planes at 200 psi. Error bars are not included.

Figure 4-29 Variation of non-dimensionalized jet width in different view planes at 250 psi. Error bars are not included.
Triangular Jets

Similar to the square orifice, the jet width in two different planes of view for the triangular orifice remain nearly the same up to 35 psi.

Figure 4-30 Variation of non-dimensionalized jet width in different view planes at 0 psi.

Figure 4-31 Variation of non-dimensionalized jet width in different view planes at 5 psi. Error bars are not included.
Figure 4.32 Variation of non-dimensionalized jet width in different view planes at 10 psi. Error bars are not included.

Figure 4.33 Variation of non-dimensionalized jet width in different view planes at 15 psi. Error bars are not included.
Figure 4-34 Variation of non-dimensionalized jet width in different view planes at 35 psi. Error bars are not included.

Figure 4-35 Variation of non-dimensionalized jet width in different view planes at 50 psi. Error bars are not included.
At 50 psi, the jet widths in the two planes are same at the orifice exit. Further downstream, one of the widths (‘TS’ plane) increases while the other (‘TV’ plane) decreases.

![Graph showing variation of non-dimensionalized jet width in different view planes at 200 psi. Error bars are not included.](image)

Figure 4-36 Variation of non-dimensionalized jet width in different view planes at 200 psi. Error bars are not included.

![Graph showing variation of non-dimensionalized jet width in different view planes at 250 psi. Error bars are not included.](image)

Figure 4-37 Variation of non-dimensionalized jet width in different view planes at 250 psi. Error bars are not included.
At 200 psi, it can be seen that the jet widths in the two planes are same at the orifice exit. Further, ‘TV’ width is greater than ‘TS’ width. As the jet moves downwards, both the jets become equal. Further downstream the ‘TS’ width continues to grow while ‘TV’ width grows at a lower rate and thus, is smaller than the ‘TS’ width. Since the triangular orifice does not have any kind of symmetry in its geometry, the behavior observed is slightly different from the square orifice. As a result, at 250 psi, the jet widths are equal at the jet origin and increase along the jet axis with different rates but this time, the rate of growth of ‘TV’ width is higher. The location, where the difference between the jet widths is the maximum, corresponds to the crest of the spatial wave as mentioned earlier in the case of rectangular orifice. Similarly, the point where the widths in different planes are equal corresponds to the neck. The distance between the crest and the neck represents half of the wavelength of the spatial wave. It has been discussed earlier that the wavelength of the spatial wave introduced due to axis switching increases with $W_eL$. A similar trend can be seen from the given charts. The distance between two necks or two crests or between a neck and a crest is increasing with the increase in $W_eL$.

Thus, for injection pressures of 35 psi and below, the axis switching phenomenon is not present in the square and the triangular orifice and the jets behave like a cylindrical jet. As a result, even the breakup lengths of the jet are same as the circular jets under similar flow conditions. As axis switching phenomenon becomes visible at injection pressures of 50 psi and above, the behavior of the square and triangular jets begin to differ from the circular jets. As a result, a deviation in the jet breakup length behavior can be observed at these flow conditions.
conditions. Thus, it can be concluded that non-circular geometry results in the axis-switching phenomenon which introduces enhanced instability in the jets thereby leading to shorter breakup lengths and faster and more severe jet disintegration.

**Droplet Size**

An attempt has been made to measure the droplet size for the different jets at different flow conditions. An equivalent diameter based upon the pixel area of the drop has been calculated. The droplet size could be measured only for injection pressures up to 250 psi as for higher injection pressures the jets entered the second wind induced regime and as a result, a large number of small droplets were produced in each case. Thus, it became difficult to separate each droplet and measure its size. As mentioned, up to 250 psi, the jets are under the Rayleigh and first–wind induced regime. As a result, the drops generated are comparable to the jet diameter. Moreover, as mentioned earlier, with increase in $We_L$, the jets tend to breakup in the form of ligaments in place of droplets. An equivalent diameter similar to the droplet diameter is calculated even for the ligaments based on their pixel area. Since, the breakup length is increasing with the increasing $We_L$, for higher injection pressures from 100 to 250 psi, the breakup length covers majority of the length of the image frame. Hence, many a times no droplets were captured in the image and only ligaments are present. Even secondary breakup of such ligaments could not be captured. The diameter at these flow conditions represent the size of the ligament produced. As a result, the diameter is increasing with the injection pressure as the ligament size increases with increase in injection pressure. The diameter measured does not represent the actual size of the droplets but is a measure of the volume of the liquid shredded from the liquid jet. The comparison of this droplet
diameter can be inferred as a measure of jet instability. Highly unstable jets disintegrate more and thus, shred more volume of liquid while the jets which are comparatively less unstable keep their core intact and generate smaller droplets and ligaments.

The value plotted for a given flow condition is the average of the diameters of all the generated droplets and ligaments. Since for each case a large number of droplets were generated and the variation in diameter among the droplets and the ligaments was high, the error bars of this particular plot are very high.

Figure 4-38 Variation of droplet size under different flow conditions of the low pressure jets
This completes the analysis of the low pressure water jets from the non-circular orifices. It has enabled us to understand the basic processes occurring during breakup of non-circular jets and the differences in their instability mechanism from circular jets.

**High Pressure Analysis**

In order to understand the differences in the characteristics of the sprays obtained from non-circular orifices, variation of microscopic property like Sauter Mean Diameter (SMD) in the axial direction and macroscopic properties like spray angle, spray tip penetration, spray tip velocity, spray volume and spray width have been measured and compared with those obtained from the circular sprays.

As mentioned earlier, the droplet size or SMD has been measured using the laser diffraction system from Malvern. For the measurement of the macroscopic properties images of the sprays were captured using high speed camera. Similar to the low pressure analysis, in order to understand the effects of the non-circular geometry on the spray pattern, all the properties have been measured from different orientations. In case of rectangular orifice, the view planes observed include the view ‘RL’, looking at the longer side of the rectangle and the view ‘RS’, looking at the shorter side of the rectangle. The square geometry has been observed from 3 different view planes. Two view planes include observations from two perpendicular sides of the square; these are referred to as view ‘SF’ and ‘SS’. The third view plane looks at the square geometry along one of its diagonals, i.e. through one of the vertices. This view is named as ‘SV’. For triangular orifice, measurements were taken in two different directions, one looking at one of the sides, view ‘TS’ and the other looking at one of the vertices, view ‘TV’.
For the measurement of macroscopic properties, the images captured were again processed and analyzed using the *Image Processing Toolbox* of MATLAB. After required cropping and contrast adjustment, the images were subjected to edge detection using *sobel* operator. Filters were used, whenever necessary, to improve the image quality. For each spray, 5 shots comprising of 50 frames were captured. The resolution is same for all the cases. Properties presented are the average of those obtained from all 5 shots.

**Development of Spray with Time**

The diesel fuel was sprayed at different injection pressures for a period of 2 ms. The high speed camera was capable of capturing the spray images for a period of more than 6 ms. Images are provided for the sprays injected at 1000 bars as obtained from different geometrical orifices at different instances of time. Common image frames of dimensions, 20 x 120 mm were used for all the cases.
Circular Orifice:

Figure 4-39 Development of spray injected at 1000 bars from circular orifice with time. Image frame dimensions: 20 x 120 mm.
Rectangular Orifice: As viewed from the longer side.

Figure 4-40 Development of spray injected at 1000 bars from rectangular orifice with time as viewed from the longer side. Image frame dimensions: 20 x 120 mm.
Rectangular Orifice: As viewed from the shorter side.

Figure 4-41 Development of spray injected at 1000 bars from rectangular orifice with time as viewed from the shorter side. Image frame dimensions: 20 x 120 mm.
Square Orifice: As viewed from one side.

Figure 4-42. Development of spray injected at 1000 bars from square orifice with time as viewed from one of the sides. Image frame dimensions: 20 x 120 mm.
Square Orifice: As viewed from another perpendicular side.

Figure 4-43. Development of spray injected at 1000 bars from square orifice with time as viewed from another side perpendicular to the previous side. Image frame dimensions: 20 x 120 mm.
**Square Orifice:** As viewed from one vertex.

![Square Orifice Diagram](image)

Figure 4-44 Development of spray injected at 1000 bars from square orifice with time as viewed from one of the vertices. Image frame dimensions: 20 x 120 mm.
Triangular Orifice: As viewed from a side.

Figure 4-45 Development of spray injected at 1000 bars from triangular orifice with time as viewed from one of the sides. Image frame dimensions: 20 x 120 mm.
Triangular Orifice: As viewed from a vertex.

Figure 4-46 Development of spray injected at 1000 bars from triangular orifice with time as viewed from one of the vertices. Image frame dimensions: 20 x 120 mm.
Macroscopic Spray Properties

Spray Width

As seen earlier, the low pressure jets emanated from non-circular orifice exhibit axis switching phenomenon. In an attempt to verify the existence of axis switching phenomenon at high injection pressures, once again, the same ideology of plotting the spray width along the spray axis is used. The spray width could be calculated only for the portion of the spray captured in the image frame. In order to eliminate the differences in the orifice cross sections, the measured widths have been normalized using the hydraulic diameters.

Spray from Rectangular Orifice

The measured spray widths have been plotted for each injection pressure and compared with the circular spray width for that pressure.

![Figure 4-47 Variation of non-dimensionalized spray width in different view planes at 300 bars for rectangular orifice.](image)
Figure 4-48 Variation of non-dimensionalized spray width in different view planes at 400 bars for rectangular orifice.

Figure 4-49 Variation of non-dimensionalized spray width in different view planes at 500 bars for rectangular orifice.
Figure 4-50 Variation of non-dimensionalized spray width in different view planes at 600 bars for rectangular orifice.

Figure 4-51 Variation of non-dimensionalized spray width in different view planes at 700 bars for rectangular orifice.
Figure 4-52 Variation of non-dimensionalized spray width in different view planes at 800 bars for rectangular orifice.

Figure 4-53 Variation of non-dimensionalized spray width in different view planes at 900 bars for rectangular orifice.
It can be seen from the charts that the width of the circular spray increases linearly along the spray axis. This is because of the spray symmetry. However, for the rectangular spray, the widths noted from different planes do not show linear variation. The widths are different in all three planes and grow as the spray moves downstream. However, the rate of growth is different for all the three widths and eventually they become nearly equal and attain an almost circular cross section. Beyond this point the width begin to differ again. Thus, it can be interpreted that the jet is undergoing axis switching even at injection pressures as high as 1000 bars. Similar results were obtained by Ho and Gutmark and Xi et al [64, 62] for elliptic jets. For low pressure jets, axis switching is a result of the competition between surface tension and inertia forces. However, in order to determine the reasons behind the high pressure jets exhibiting the axis switching a detailed inspection of the spray structure and its interaction with the surrounding gas is required. This has not been covered in the present
work. According to Batchelor [83], lateral flapping in high pressure sprays is the result of vortex deformation due to self–induction. This mechanism is one of the reasons of increased air entrainment. Another mechanism is bifurcation [66] which is seen in only from geometries with aspect ratio effects. As noted in the case of low pressure jets, it can be seen that the distance of the location from the orifice, where all the three widths are equal increases with increase in injection pressure. Hence, the wavelength of the axis switching increases with increase in injection pressure.

One may point out that since with time the spray grows out of the frame, at the end of the frame all three widths may coincide. However, this is not the case here. The frame width is 20 mm and the maximum width attained by the spray is less than 20 mm in all the view planes. Moreover, the widths have coincided at a distance prior to the end of the frame. Thus, the equal value of the widths indeed represents the circular cross section.

Also, it should be noted that the spray width of the rectangular jet is greater than the circular jet at all the injection pressures and in all the view planes. This indicates a greater spray angle and a larger spray volume for the rectangular sprays. This, in turn, indicates better air entrainment for the rectangular sprays.
Spray from Square – shaped Orifice

The variation of the spray width of the square spray at different injection pressures and from different view planes in plotted. It can be seen that all the injection pressures the width at the orifice exit in all three view planes is the same, i.e. the spray comes out with a circular cross section. Also, this width is greater than the width of the circular spray. For injection pressures up to 600 bars, as the spray moves downstream it departs away from its circular cross section and for pressures 300 to 500 bars, the spray width even becomes lesser than the circular width at about 80 mm from the nozzle.
Figure 4-56 Variation of non-dimensionalized spray width in different view planes at 300 bars for square orifice.

Figure 4-57 Variation of non-dimensionalized spray width in different view planes at 400 bars for square orifice.
Figure 4-58 Variation of non-dimensionalized spray width in different view planes at 500 bars for square orifice.

Figure 4-59 Variation of non-dimensionalized spray width in different view planes at 600 bars for square orifice.
Figure 4-60 Variation of non-dimensionalized spray width in different view planes at 700 bars for square orifice.

Figure 4-61 Variation of non-dimensionalized spray width in different view planes at 800 bars for square orifice.
For pressures above 600 bars, the spray width is nearly the same in all the view planes and increases linearly along the spray axis similar to the circular spray. This can also be seen
from the images shown in Figure 4-55. Thus, beyond 600 bars, the axis switching phenomenon cannot be observed and the spray becomes circular. Thus, the strong interaction between the liquid inertia (owing to high injection pressure), turbulence and aerodynamic conditions suppresses the axis switching phenomenon. But still, the spray width is greater than the spray width obtained from the circular orifice throughout the axial length.

Figure 4-64 Comparison of spray widths of square sprays in different view planes.
Triangular Sprays

The variation of the spray width in the two view planes clearly indicates the existence of axis – switching phenomenon in triangular sprays. At all the injection pressures, the widths in the two planes are nearly the same. However, as the spray travels downstream, the difference between them increases. Thus, the spray is not symmetric along the spray axis. The width grows linearly in both the view planes; however, the rate of growth is different. It’s higher in the ‘TS’ plane and thus, the spray is wider. For pressures above 500 bars, the two widths again become equal at about 10 cms away from the nozzle. This can be seen in the images shown in Figure 4-56.

![Figure 4-65 Comparison of spray widths of triangular sprays in different view planes.](image)

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With respect to the circular sprays, the triangular sprays are wider in both the view planes under every flow condition.

Figure 4-66 Variation of non-dimensionalized spray width in different view planes at 300 bars for triangular orifice.

Figure 4-67 Variation of non-dimensionalized spray width in different view planes at 400 bars for triangular orifice.
Figure 4-68 Variation of non-dimensionalized spray width in different view planes at 500 bars for triangular orifice.

Figure 4-69 Variation of non-dimensionalized spray width in different view planes at 600 bars for triangular orifice.
Figure 4-70 Variation of non-dimensionalized spray width in different view planes at 700 bars for triangular orifice.

Figure 4-71 Variation of non-dimensionalized spray width in different view planes at 800 bars for triangular orifice.
Though both square and triangular geometries lack the aspect ratio effect but still the triangular sprays demonstrate axis switching at all flow conditions while the square sprays
exhibit it at lower injection pressures only. This can be attributed to the acute angularity of the triangular orifice which renders sharp curvature to the shape.

**Spray Cone Angle**

For the measurement of spray cone angle, after carrying out the edge detection, a linear polynomial fit for the images was calculated and plotted on the edges themselves to check for the correctness of the linear fit. The angle between these two lines was then measured and has been interpreted as the spray cone angle. Several different definitions of spray cone angle exist in the literature and we choose the angle of injector tip and two points on the spray periphery located at one third of spray penetration as our measurement target. This definition was introduced by He *et al.* [80] in their work of spray cone angle measurement. However, we have measured the cone angle for two different locations, one up to 20 mm from the nozzle tip and the other up to 80 mm from the nozzle tip, in order to understand the complete development of the spray along the spray axis. Images are provided to demonstrate the procedure of measurement. The images belong to the sprays injected at 1000 bars and were captured nearly 1.7 ms after the start of injection. Values in ‘red’ correspond to the 20 mm location while those in ‘blue’ correspond to the 80 mm location.

As the spray is ejected out of the injector, it evolves and its cone angle changes with time. For a better comprehension, variation of the spray angles with time for different orifices from different directions is presented. These are the cone angle values measured at 20 mm from the nozzle orifice. This also allows one to carry out the comparison between the development of non-circular and circular sprays.
Figure 4-74 Demonstration of the procedure of measurement of cone angles at two different locations. (a) Circular spray,  (b) RL view, (c) RS view, (d) SF view, (e) SS view, (f) SV view, (g) TS view, (h) TV view. Injection pressure: 1000 bars. ASOI: 1.71 ms.
Figure 4-75 Variation of spray cone angle in different view planes at 20 mm for 300 bars. Errors not included.

Figure 4-76 Variation of spray cone angle in different view planes at 20 mm for 400 bars. Errors not included.
Figure 4-77 Variation of spray cone angle in different view planes at 20 mm for 500 bars. Errors not included.

Figure 4-78 Variation of spray cone angle in different view planes at 20 mm for 600 bars. Errors not included.
Figure 4-79 Variation of spray cone angle in different view planes at 20 mm for 700 bars. Errors not included.

Figure 4-80 Variation of spray cone angle in different view planes at 20 mm for 800 bars. Errors not included.
It can be seen from the charts that as the jet is injected the spray angle is initially very high but then in drops suddenly and then remains nearly constant. As the liquid is sprayed in a gas
environment, the liquid drops exchange momentum with the surrounding gas. Due to the aerodynamic drag, the drops decelerate and the momentum lost by the drops is acquired by the gas. Moreover, as the kinetic energy of the spray is very high, the pressure energy of the flow is less in accordance with the Bernoulli’s principle. Thus, a flow field is created where gas is continually entrained into the spray. As the gas entrains the spray, the gas molecules drag the spray particles on the spray periphery inwards, causing the spray to contract. As per Rothe and Block [81], the magnitude of the contraction depends on how effectively the spray drops entrain the gas, and on how strongly the inflowing gas pushes the drops from their original trajectories. These effects, in turn, depend on parameters such as original spray kinetic energy (set in part by nozzle pressure), total flow rate, drop size, and ambient gas density.

Once the spray has fully developed and attained a steady state the cone angle remains nearly constant. If different geometries are compared, it can be seen that the spray cone angle is maximum for the rectangular orifice in the ‘RS’ view plane. The angle is greater than the cone angle in ‘RL’ view. Similar, results were obtained by [60]. It is possible that the spray has switched its axes within this distance from the orifice and thus, the spray angle is greater in the ‘RS’ view. This is in agreement with the spray width data as well, in which the spray width is slightly greater in the ‘RS’ view than in the ‘RL’ view at all injection pressures. Thus, the spray angle is the maximum in the ‘RS’ view. It is followed by the spray angles obtained from the square orifice. The three view planes of the square orifice are in close range, similar to the trend shown by their spray widths. They are followed by the spray
angles in ‘RL’ view. The cone angle for circular orifice and the triangular orifice differ by only 1 or 2 degrees.

Since the non-circular orifices undergo axis switching, as a result, difference in the trends of spray angles at 80 mm location are expected. This can be seen in the charts provided below. It should be noted that these charts are plotted only for the steady state of the spray. This is because the spray is not developed fully along the entire length simultaneously. By the time the initial spray length has developed, the later portions are still evolving. Thus, initial images of the 80 mm location show erratic spray angles. This is evident from the charts of 300 – 500 bars of pressure where depending upon the spray tip velocity; slower sprays have not achieved steady state in the plotted at the beginning of the plotted time interval. At higher injection pressures, because of high spray tip velocity, all sprays are in their steady state.

![Figure 4-83 Variation of spray cone angle in different view planes at 80 mm for 300 bars. Errors not included.](image-url)
Figure 4-84 Variation of spray cone angle in different view planes at 80 mm for 400 bars. Errors not included.

Figure 4-85 Variation of spray cone angle in different view planes at 80 mm for 500 bars. Errors not included.
Figure 4-86 Variation of spray cone angle in different view planes at 80 mm for 600 bars. Errors not included.

Figure 4-87 Variation of spray cone angle in different view planes at 80 mm for 700 bars. Errors not included.
Figure 4-88 Variation of spray cone angle in different view planes at 80 mm for 800 bars. Errors not included.

Figure 4-89 Variation of spray cone angle in different view planes at 80 mm for 900 bars. Errors not included.
As expected, due to the axis switching phenomenon, at 80 mm, the spray angle of ‘RL’ view is the maximum. It is followed by the spray angle in ‘RS’ view, the spray angles for the square sprays and lastly, by the circular and triangular sprays. The differences between the circular and triangular spray angles have further reduced. Although the spray angle for ‘RL’ is greater, for a given flow condition it is still lesser than the spray angle of the ‘RS’ view at 20 mm location.

In order to determine the effect of the injection pressure on the spray angle, the values have been plotted for different orifices under different flow conditions. These are shown in Figure 4-82. Since with increase in injection pressure, the amount of fuel injected increases, as a result, the spray angle increases.
Figure 4-91 Variation of spray cone angle in different view planes with injection pressure at 20 mm.

Figure 4-92 Variation of spray cone angle in different view planes with injection pressure at 80 mm.
For the sake of better comparison between the different orifices, averages of the spray angles from different views for the non-circular orifices were calculated to get a representative value for all the geometries.

Figure 4-93 Comparison of spray cone angle from different orifices at 20 mm

Figure 4-94 Comparison of spray cone angle from different orifices at 80 mm
Thus, it is clearly visible that the spray angles are greater for the rectangular and square orifices. The triangular orifice gives spray angle lesser than the circular spray angles but this is because the area of the triangular orifice is very less than the circular orifice. Even though, the area of the triangular orifice is only 56% of the area of the circular orifice, the triangular spray angles differ from the circular spray angles by only 1 or 2 degrees. The rectangular and square orifices have comparable area with the circular orifice and they are producing wider sprays. Thus, it can be concluded that non-circular geometry produces greater spray angles as compared to the circular geometry. Since all three non-circular orifices exhibit axis switching, the greater spray angles can be attributed to this phenomenon.

**Spray Tip Penetration and Velocity**

From the processed images, the distance of the spray tip from the orifice was measured. This is the spray tip penetration. This length was then divided by the time taken by the spray to cover that distance after the start of injection to obtain the spray tip velocity. These values could only be measured for the time interval during which the spray tip could be captured within the image frame. Once the spray has grown out the image frame, it was not possible to measure these parameters. The sprays exhibited different spray tip velocities; as a result, the faster sprays grew out of the image frame earlier than others. Hence, the data is not available for all the orifices at every point of time. The spray tip velocity and its acceleration give an indication of the spray velocity profile. The plots of the spray tip penetration, velocity and acceleration are provided together for a better understanding. Considering the initial spray velocity, it can be seen at under majority of flow conditions, the circular spray is the first to
come out of the nozzle owing to its high initial acceleration as compared to other sprays. Though the fuel has been injected for duration of 2 ms; all the sprays reach a peak in their acceleration within 0.86 ms for lower injection pressures up to 500 bars and within 0.71 ms for higher injection pressures. After reaching the peak, the spray acceleration starts decreasing for the rest of the injection duration and after certain period of time even goes negative, i.e. the spray starts decelerating. However, the rate of change of acceleration is different for the sprays obtained from different geometries. As a result, differences can be noted in their velocities as well as penetrations.

![Comparison of spray tip penetration obtained from different orifices at 300 bars.](image)

Figure 4-95 Comparison of spray tip penetration obtained from different orifices at 300 bars.
At 300 bars, it can be seen that the rate of increase in acceleration is very high for all the sprays; however, it is the highest for the circular spray. Thus, its tip velocity is higher and so
is the penetration. After reaching the peak, the acceleration starts decreasing for all the sprays. But the rate of decrease is the highest in case of rectangular sprays and lowest in the triangular sprays. As a result, the spray tip velocity of rectangular spray increases at a lower rate and even starts decreasing after some time while for others it increases at a higher rate. This explains the shorter penetration of the rectangular sprays as compared to sprays from other geometries. Being the slowest, the rectangular spray takes the maximum time in growing out of the image frame and hence, its penetration data is available for longer time durations while others have already grown out of the frame.

With regards to the circular, square and triangular geometry, the rate of increase in acceleration is highest for the circular sprays for all flow conditions but the rate of decrease is nearly the same for all three geometries. As a result, penetration of the circular sprays is slightly higher than the square and triangular sprays with minor variation in the trend.

![Figure 4-98 Comparison of spray tip penetration obtained from different orifices at 400 bars.](image)
Figure 4-99 Comparison of spray tip velocity obtained from different orifices at 400 bars.

Figure 4-100 Comparison of spray tip acceleration obtained from different orifices at 400 bars.
Figure 4-101 Comparison of spray tip penetration obtained from different orifices at 500 bars.

Figure 4-102 Comparison of spray tip velocity obtained from different orifices at 500 bars.
Figure 4-103 Comparison of spray tip acceleration obtained from different orifices at 500 bars.

Figure 4-104 Comparison of spray tip penetration obtained from different orifices at 600 bars.
Figure 4-105 Comparison of spray tip velocity obtained from different orifices at 600 bars.

Figure 4-106 Comparison of spray tip acceleration obtained from different orifices at 600 bars.
Figure 4-107 Comparison of spray tip penetration obtained from different orifices at 700 bars.

Figure 4-108 Comparison of spray tip velocity obtained from different orifices at 700 bars.
Figure 4-109 Comparison of spray tip acceleration obtained from different orifices at 700 bars.

Figure 4-110 Comparison of spray tip penetration obtained from different orifices at 800 bars.
Figure 4-111 Comparison of spray tip velocity obtained from different orifices at 800 bars.

Figure 4-112 Comparison of spray tip acceleration obtained from different orifices at 800 bars.
Figure 4-113 Comparison of spray tip penetration obtained from different orifices at 900 bars.

Figure 4-114 Comparison of spray tip velocity obtained from different orifices at 900 bars.
Figure 4-115 Comparison of spray tip acceleration obtained from different orifices at 900 bars.

Figure 4-116 Comparison of spray tip penetration obtained from different orifices at 1000 bars.
For a better explanation, detailed study of the aerodynamic behavior of the sprays is needed. But still, some inferences can be drawn from the spray width data presented earlier. It was
noted earlier that all the sprays from the non-circular geometries have widths greater than the circular sprays at distances beyond 80 mm from the nozzle tip in all the view planes. As a result, the sprays tend to have a greater surface area and a larger cross section. Thus, the aerodynamic drag acts on a larger surface area for the non-circular sprays than the circular ones. This greater opposition from the atmosphere can explain the slower spray velocities, especially for the rectangular sprays which have the maximum widths and the greatest cone angles and thus, the slowest velocities and the smallest penetrations.

**Spray Volume**

Using the comprehensive data of spray tip penetration and cone angle, we can calculate the spray volume by using Equation (4.5) developed by Delacourt [82].

\[
V = \left(\frac{\pi}{3}\right)S^3 \left(\tan^2\left(\frac{\theta}{2}\right)\right) \left(\frac{1 + 2\tan\left(\frac{\theta}{2}\right)}{1 + \tan\left(\frac{\theta}{2}\right)}\right)^3
\]

(4.5)

where, \(S\) is the spray tip penetration and \(\theta\) is the cone angle of spray. The spray volume \(V\) is in mm\(^3\).

The variation of the spray volume obtained from different orifices at different injection pressures is presented.
Figure 4-119 Comparison of spray volume obtained in different view planes at 300 bars.

Figure 4-120 Comparison of spray volume obtained in different view planes at 600 bars.
Figure 4-121 Comparison of spray volume obtained in different view planes at 800 bars.

Figure 4-122 Comparison of spray volume obtained in different view planes at 1000 bars.
Since a circular spray remains symmetric about its axis, the spray volume represents the 3 – dimensional geometry of the spray. However, in case of sprays obtained from the non - circular orifices, since the spray geometry is different in different view planes, the value of the spray volume obtained represents the space occupied in that dimension only and does not represent the 3 – dimensional geometry.

The combined effect of the spray tip penetrations and the spray angles can be seen in the chart provided for 300 bar injection pressure. As the spray evolves with time, it can be seen that since the spray angle in “RS’ view plane was nearly the double of the spray angles obtained from different orifices in different view planes, thus, despite of its shorter penetration, the rectangular spray has the largest spray volume in this view. The “SV’ view has the highest spray angles in all the view planes of the square orifice, the penetration being the same in all the three view, ‘SV’ has the largest spray volume. It is even larger than the spray volumes for circular and triangular sprays and the rectangular spray in ‘RL’ view plane. For pressures above 600 bars, the spray volume of ‘SV’ plane is larger even than the ‘RS’ plane. As the spray develops, it was noted in the spray angle section, that in the ‘RS’ plane the spray angle reduces, i.e. the spray angle was higher at 20 mm location than the 80 mm location. This means that the spray is contracting beyond 80mm. If the spray width data is considered, it can be seen that for pressures above 600 bars axis switching phenomenon has been observed to occur in this region. As a result, as the spray undergoes lateral flapping the spray width and the spray angle reduces. This gets reflected in the spray volume calculations as well. For pressures below 600 bars the rectangular sprays acquire circular cross section at around 60mm from the nozzle tip. Beyond this point the spray again expands.
For pressures above 600 bars, the circular cross section is assumed at around 80 mm which tends to occur near the end of the frame; as a result any expansion occurring thereafter has not been recorded. Thus, the spray volume becomes smaller than that observed in ’SV’ plane under these flow conditions. While the rectangular and square spray volumes are higher than the circular sprays, the spray volume obtained for triangular sprays are considerably less. This is due to the cross sectional area of the triangular orifice which is slightly more than the 50 % of the area of the circular orifice. As a result, the mass of fuel injected is less and so is the spray volume.

For a better comparison and to get the idea of the entire volume of the 3 – dimensional spray structures, average of the volumes from different planes was measured for each orifice. These are presented in Figure 4-114 to 121.

![Graph showing comparison of spray volume obtained from different orifices at 300 bars.](image)

Figure 4-123 Comparison of spray volume obtained from different orifices at 300 bars.
Figure 4-124 Comparison of spray volume obtained from different orifices at 400 bars.

Figure 4-125 Comparison of spray volume obtained from different orifices at 500 bars.
Figure 4-126 Comparison of spray volume obtained from different orifices at 600 bars.

Figure 4-127 Comparison of spray volume obtained from different orifices at 700 bars.
Figure 4-128 Comparison of spray volume obtained from different orifices at 800 bars.

Figure 4-129 Comparison of spray volume obtained from different orifices at 900 bars.
It can be seen that, with increase in injection pressure, the sprays are attaining their steady states early. As a result, the data is available for shorter periods of time at higher injection pressures. These charts are in agreement with the comments made above regarding the variation of spray volume of rectangular sprays. For pressures below 600 bars, the rectangular spray volume is higher than the square spray volumes. For higher injection pressures, the square sprays occupy greater volumes. Under all the high pressure flow conditions, the non–circular geometries (with the exception of triangular orifice) are generating spray volume more than the circular sprays. This is an indication of better air entrainment and mixing in case of non-circular sprays as compared to the circular sprays owing to the larger spray widths and hence, larger surface area.
Microscopic Spray properties

Sauter Mean Diameter

The SMD of the sprays form different orifices is measured for varying flow conditions using the laser diffraction system from Malvern. Determination of droplets size determines the extent of atomization achieved. In order to understand the atomization process occurring in the non-circular sprays, the droplet size has been measured at different locations along the jet axis, i.e. in the axial direction. For each flow condition and location, the SMD was measured for 10 different sprays. The values presented are, thus, an average of 10 different runs. The axial location of measurement was varied by 10 mm for all the injection pressures except at 700 bars. For a better study of the spray plume, the axial locations were varied by 5mm for the injection pressure of 700 bars.

Droplet Size Analysis in Axial Direction

For droplet size measurement in the axial direction, tests were conducted at different locations. For each location the injection pressure is varied to study the effect of increasing injection pressure. Studies have shown that the droplet size varies inversely with the injection pressure [76]. As the injection pressure increases the size of the droplets produced reduces. But as these droplets travel further, they tend to coalesce. As a result, at distances farther from the nozzle tip, the droplet size increases. The size increases up to a certain limit beyond which due to bigger size, hence, greater mass and high velocity owing to high injection pressure, the drops undergo secondary atomization. Thus, with distance the size reduces again. This is similar to the trend observed in low pressure jets where the droplets agglomerate and later undergo secondary breakdown [32].
As it is clear by now, that as the non-circular sprays develop in space they periodically undergo axis-switching. As a result, the spray geometry is not uniform. While at some location, the spray is expanding or increasing its width, at the others it may be undergoing contraction. Due to asymmetric geometric development, the interaction of the spray with ambient gases varies at different locations. Hence, besides injection pressure droplet size also depends on the location where measurement is taken. Moreover, it has been showed that the spray accelerates only for a small duration during the injection and for the major part of time undergoes deceleration. It can be concluded that the spray evolves both spatially as well as temporally. Thus, measurements were taken at different locations but the values presented for each location is the time-averaged value of all the measurements recorded during the injection period at a given location. For a given pressure, with variation in location, the extent of axis-switching the spray has undergone changes, the spray velocity changes and thus, the aerodynamic interaction changes. Thus, the droplets may be coalescing due to spray contraction or breaking down due to spray diffusion with location. Thus, it becomes difficult to identify any particular trend in the droplet size with variation in location. For simplicity, variation in droplet size with pressure for given location has been given more importance. Droplet size was measured in terms of Sauter Mean Diameter (SMD). Sauter Mean Diameter (SMD, also known as $d_{32}$) is equal to the sum of the cube of all diameters of measured droplets divided by the sum of the square of all diameters. This yields a characteristic droplet diameter which has a volume to surface area ratio equal that of the entire spray [85]. The results obtained are provided below.
Figure 4-131 Variation of non-dimensionalized droplet size with injection pressure for circular sprays.

Figure 4-132 Variation of non-dimensionalized droplet size with injection pressure in RL view.
Figure 4-133 Variation of non-dimensionalized droplet size with injection pressure in RS view.

Figure 4-134 Variation of non-dimensionalized droplet size with injection pressure in RV view.
Figure 4-135 Variation of non-dimensionalized droplet size with injection pressure in SF view.

Figure 4-136 Variation of non-dimensionalized droplet size with injection pressure in SS view.
Figure 4-137 Variation of non-dimensionalized droplet size with injection pressure in SV view.

Figure 4-138 Variation of non-dimensionalized droplet size with injection pressure in TS view.
Figure 4.139 Variation of non-dimensionalized droplet size with injection pressure in TV view.

All the charts show a similar trend for the variation of non-dimensionalized droplet size with increase in pressure. For pressures from 300 to 500 bars, the droplet size decreases but for higher injection pressures it increases in a non-linear manner. This can be attributed to the phenomenon of droplet coalescence. In some cases, the drops after agglomeration can be seen to undergoing secondary atomization as the droplet size after reaching a peak again decreases. However, no particular trend can be observed if for a given pressure the variation of droplet is considered with change in axial location.

For comparison between circular and non-circular sprays, data is provided for two different locations, 50 mm and 80 mm from the nozzle tip.
Triangular sprays are giving very high values. This is because the hydraulic diameter is the smallest for the triangular orifice and therefore, after normalization the scale reverses. At 50
mm, it can be seen that for pressures below 600 bars the droplets obtained from circular
sprays are bigger than those from rectangular and square orifices. For higher injection
pressures, on the other hand, the non-circular orifices are giving bigger droplets. At 80 mm,
the normalized droplet size is nearly the same for the orifices except the triangular case for
injection pressures up to 500 bars. At higher injection pressures, the droplet size decreases
for the circular sprays in comparison to the non-circular sprays.

For a better explanation of the variation in droplet size with location it is necessary to study
the aerodynamic behavior of the spray. Also, velocity distribution within the spray plume is
required to determine the droplet collision phenomenon. Both of these areas have not been
covered in this work.
CHAPTER 5: CONCLUSIONS

The effect of the non–circular orifices on the spray characteristics of diesel fuel are evaluated experimentally. The fuel was injected using a high pressure common rail system at atmospheric pressure conditions at injection pressures varying from 300 to 1000 bars. Special diesel fuel injector nozzles were fabricated via an electro discharge machining (EDM) process using stainless steel. High pressure fuel breakup is a complex phenomenon; hence, for a better understanding of the underlying physical processes involved, the effect of non–circular orifice geometry was also analyzed at low pressures from 0 to 1000 psi. The low pressure orifice discs employed for were also fabricated using the EDM process. Care was taken in each case that the cross sectional area of all the orifices are nearly the same. However, the area of the high pressure diesel injector nozzle with triangular orifice was considerably less. It was nearly 55% of the area of the circular orifice. The low pressure jets and high pressure sprays obtained from the non–circular orifices were analyzed from different directions using the high speed camera.

The breakup phenomenon has been characterized by measuring the breakup lengths and droplet size of the low pressure jets obtained from the non–circular orifices. Depending on the gas Weber number different breakup regimes were identified and it was observed that under the experimental flow conditions, the jets experienced the Rayleigh, the first – wind induced and the second wind induced breakup regimes under the experimental flow conditions. The flow behavior has been characterized using the non-dimensional parameters like the Reynolds number and the Weber number. The non - circular jets demonstrated enhanced unstable behavior and exhibited faster breakup process as compared to the
corresponding circular jets. The breakup lengths for the non-circular jets tended to coincide with each other and were markedly smaller than the breakup lengths of the circular jets. Moreover, the rectangular jets prominently displayed the axis-switching phenomenon. The square and triangular jets behaved like the circular jets for a specific range of flow conditions and did not display the axis-switching process. For the flow conditions away from this range, the square and triangular jets behavior deviated from the circular jet behavior and exhibited faster breakup process. However, the axis-switching phenomenon was not visible under any flow conditions for the square and triangular jets. Thus, in order to determine the existence of the axis-switching phenomenon in square and triangular jets, the jet widths of the non-circular jets were plotted up to the jet breakup length. For injection pressures up to 35 psi, the widths in different view plans were equal indicating the circular jet-like behavior. For higher injection pressures, variations in the jet widths were obtained in the different view planes which proved the existence of the axis-switching phenomenon in the square and triangular jets. The phenomenon was prominently visible in the rectangular jets due to its aspect ratio effect of geometry. The faster jet breakup observed in non-circular jets is thus, attributed to the inertia-driven axis-switching phenomenon. Moreover, it can be inferred that the non-circular orifice geometry induces greater instabilities in the jet and cause it to disintegrate faster.

An attempt was made to determine the droplet size of the non-circular jets based on their pixel area in the images. It was noted that with the increase in $We_2$, the jets tend to breakup in the form of ligaments. These ligaments are further subjected to breakup and disintegrate into smaller droplets. As a result, based on the portions of the jets captured in the image frame, it
was observed that with increase in the injection pressure, the jets showed an increased tendency towards breaking up in the form of ligaments. The triangular jets produced the biggest ligaments. This indicates the tendency of the triangular jets of shredding large volumes of jets in the form of ligaments and points towards the highly unstable jet behavior. This can be attributed to the sharp corner angles of the triangular shape. Although corners are present in rectangular and square jets as well, the radius of curvature is more. Under the experimental flow conditions, the most unstable behavior was demonstrated by the triangular orifice.

After gaining a basic understanding of the jet breakup phenomenon, the high pressure analysis was carried out using a high pressure common rail diesel injection system discharging diesel sprays at 300 to 1000 bars. For comparing the spray characteristics of the non-circular sprays with the circular sprays, properties like spray width, cone angle, tip penetration and velocity, volume and droplet size in the axial direction have been measured from different directions.

By plotting the spray widths of the non-circular sprays along the spray axis, it was demonstrated that the even at such high injection pressures, the non-circular sprays undergo axis switching. The rectangular sprays exhibited the largest spray widths, and thus, have the largest surface area. Square orifices demonstrated the axis switching phenomenon for injection pressures up to 500 bars only. For higher pressures, the square jets assumed nearly circular cross section. The widths of the square sprays were greater than the circular jets. Even though the triangular orifice has a considerably smaller area than the circular orifice, it
exhibited greater widths than the circular sprays. Axis switching was present in the triangular sprays under all the injection conditions.

Spray angle was measured for all the sprays at two different locations, 20 mm and 80 mm along the spray axis. Similar to the spray width, the rectangular sprays exhibited the greatest spray angles followed by the square sprays, the circular sprays and the triangular sprays. For injection pressures above 600 bars, the spray angles of the rectangular sprays were smaller at the 80 mm location than those obtained at the 20 mm location. This was due to the contraction of the spray occurring because of the spray assumed circular cross section due to the axis switching phenomenon at around 80 mm location.

Spray tip penetration, velocity and acceleration were calculated for the injection duration during which the spray tip was present within the image frame. It was noted that the spray acceleration initially increased, reached a peak and then started decreasing for all the sprays. The rate of increase of the spray acceleration was the highest for the circular sprays and the lowest for the rectangular sprays while the rate of decrease in acceleration was the highest for the rectangular sprays. As a result, the circular, square and triangular sprays showed longer penetrations than the rectangular sprays. To explain these results, a better understanding of the aerodynamic behavior of the sprays is required which was not covered in this work. However, it can be inferred based on the spray width data available that the rectangular sprays having the largest surface areas experience the strongest aerodynamic drag thereby resulting in their shorter penetrations.

Based on the data available for the spray tip penetration and cone angles, the spray volumes for different geometric spray were calculated. Because of their larger widths and spray
angles, the rectangular sprays showed the largest spray volumes for injection pressures below 600 bars. As the rectangular sprays undergo contraction for the injection pressures above 600 bars, their spray volume falls below those obtained from the square orifices. Thus, the non-circular sprays produce greater spray volumes than the circular sprays. The spray volume of the triangular sprays is less than those of the circular spray because of their smaller cross section areas delivering lesser mass of fuel and thus, smaller spray volumes. This is an indication that the non-circular sprays produce greater spray volumes, and thus, have better air entrainment and mixing.

However, on analyzing the droplet size of the sprays it was found that the droplet size of the non-circular sprays varies with location and does not follow any particular trend. This is because the spray geometry transforms continuously along the axis. Thus, at one location the spray may undergo expansion while at other it may diffuse. And this behavior is repeated periodically along the axis. At distances closer to the nozzle, non-circular sprays give smaller droplets for injection pressures up to 500 bars. For higher pressures, droplets from circular sprays are smaller. At locations as far as 80 mm from the nozzle tip, the droplet sizes are similar for injection pressures up to 500 bars but for higher pressure, the circular sprays again give smaller droplets. For a better understanding knowledge of the spray velocity field and its aerodynamic behavior is needed.

Thus, the non-circular sprays give better performance in terms of macroscopic spray properties which yields better air entrainment and mixing. However, in terms of atomization, the droplet size obtained depends upon the location as well as the injection pressures. In
order to analyze the performance in terms of combustion, heat release rate and pollutant formation further studies in these areas are needed.
CHAPTER 6: FUTURE WORK

This work analyzed the spray characteristics of the non-circular sprays in terms of spray tip penetration, velocity, cone angle, width and volume and droplet size. In order to understand, the atomization obtained from the non-circular orifices more work is required to be done in analyzing the instabilities induced by the non-circular geometries. Theoretical analysis studying the nature of the instabilities and capable of determining the spray geometry are required. Moreover, empirical relations defining the effect of different parameters like injection pressure, orifice dimensions and others will provide a better picture of the atomization process.

In terms of experimentation, the present work was carried out at room temperature and pressure conditions. For practical applications, spray behavior in pressurized ambient condition similar to the actual engine combustion chamber should be carried out to evaluate the performance of the non-circular sprays. Furthermore, studying the aerodynamic behavior of the sprays and measurements of the spray velocity field by techniques like Particle Image Velocimetry (PIV) will enable one to determine the physical processes involved in droplet breakdown.

Numerical analyses will help to understand the flow behavior within the nozzle, the effect of cavitation and how the presence of sharp corners in some geometries affect the flow development. Thus, with a better understanding of the flow behavior of non-circular sprays better advancements can be achieved in the areas of fuel atomization and spray combustion.
CHAPTER 7: REFERENCES


