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EFFECT OF INLET TANGENTIAL PORT AREA ON THE PERFORMANCE OF SMALL – SCALE SIMPLEX ATOMIZER

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Abstract. An experimental investigation was conducted to study the effects of increased area of inlet tangential ports on the performance of small scale simplex atomizer. The spray characteristics of three different simplex atomizer representing varying area of inlet tangential ports are examined using water as a working fluid. Measurements of coefficient of discharge, spray cone angle, Sauter mean diameter and droplet size distribution were carried out over wide range of injection pressure. Coriolis mass flow meter was used to measure coefficient of discharge. Spray cone angle was measured by image processing technique. Sauter mean diameter and droplet size distributions were measured by Malvern droplet sizing instrument. It was observed that with increase in area of inlet tangential ports the size of air core produced along the center line reduced, which increases the coefficient of discharge. Spray cone angle decreases with increase in area of inlet tangential ports. It was found that increase in area of inlet tangential ports reduces swirl strength inside swirl chamber, which results in increasing Sauter mean diameter. Better droplet size distribution was observed for lower area of inlet tangential port configuration. Good agreement was observed between the obtained experimental results and experimental correlations available in literatures.

Keywords: **Simplex atomizer, Tangential port area, Sauters Mean Diameter, Droplet size distribution.**

1. INTRODUCTION

Atomization is a process of generating a large number of droplets from a bulk liquid. The performance of a liquid fuel atomizer has direct effects on combustion efficiency, pollutant emissions, and combustion flame stability. To obtain high ratios of the surface to mass in the liquid phase which leads to the desired very high evaporation rates, the liquid fuel must be fully atomized before being injected into the combustion zone. In applications where combustion rates must be high, such as, for example, in aircraft engines the spray cone angles must be large, around 90 deg, due to the need of minimizing the combustor length. This much wider cone angles can be obtained using simplex atomizer. Since the droplet size distribution and local fuel to air ratios significantly affects combustion efficiency and emissions, it is important to predict the impact of atomizer geometry on performance. Because of its advantages such as relatively simple and inexpensive to manufacture, good spray quality and simple geometry, simplex atomizers are widely used in air-breathing gas turbine combustion.The atomizer's principle of operation is simple. It consists of swirl chamber, tangential port and exit orifice as shown in figure – 1. The liquid is forced under high pressure to enter the swirl chamber through tangential ports. The tangentially introduced fluid forms a rotating flow inside the chamber. The swirl motion of the liquid pushes it close to the wall and creates a zone of low pressure along the center line. An air core is formed along the centerline as a result of this high swirl velocity of the liquid. The formation of a central air core is the most important phenomenon in a simplex nozzle. The size of the air core determines the effective flow area at the discharge orifice and thus controls the coefficient of discharge, which is one of the important performance parameter of the nozzle. The liquid exits the atomizer through a small orifice with even higher swirl velocity. Due to the tangential velocity of flow inside the injector the liquid comes out of the orifice in the form of a thin film. The thin film escaping the exit orifice is rather unstable and the slightest fluctuation will cause distortions when it is in contact with the air. As the amplitude becomes so large that the surface tension can no longer withhold the breaking force, the film will rupture into ligaments. Traveling in the air, the ligaments will further collapse into droplets.Spray cone angle determines the coverage and dispersion of spray in the surrounding environment. Smaller SMD represents effective atomization.

Lefebvre [1] has organized the most important reference on atomization and sprays, some important predictions on coefficient of discharge, spray angle, and mean droplet size in terms of liquid pressure drop, liquid viscosity, ambient density, liquid density, liquid surface tension and atomizer orifice diameter. Rizk and Lefebvre [2] developed equation for coefficient of discharge, liquid film thickness and flow number in terms of atomizer dimensions. The equation for liquid film thickness shows the film thickens with increase in orifice diameter and viscosity of liquid. Pedro Teixeira Lacava et al [3] described about percentage of total droplets volume distribution as a function of liquid pressure differential.The tendency was such that, when the pressure increased, the droplets with diameter smaller than 100 microns were increased, but droplets with diameter larger than100 microns were decreased.Ashraf A. Ibrahim and Milind A. Jog [4] predicted the breakup length (L_b) of a liquid sheet at elevated ambient pressure. They concluded that, increase in Weber number decrease the breakup length of sheet emanating from simplex atomizer, increase in area of inlet tangential ports increase the breakup length. M.A.Jog, S.M. Jeng and M.A Benjamin [5] developed a computational model to predict the characteristics of liquid sheet emanating from orifice. They concluded that, reduction in total port area increase the swirl strength inside the swirl chamber and increase the spray angle. Sakman, Jog, Jeng and Benjamin [6] conducted a numerical study to present the effects of changes in simplex nozzle geometry (L_s/ D_s, l_o / d_o and D_s/d_o) on coefficient of discharge, spray cone angle and film thickness. They concluded that, increase in swirl chamber length reduce the cone angle. Datta and S.K. Som [7] used numerical methods to predict the air core diameter, coefficient of discharge and spray cone angle. From their study, it was found that an increase in either the orifice diameter or swirl chamber angle or decrease in area of inlet tangential ports increased the air core diameter and spray cone angle.

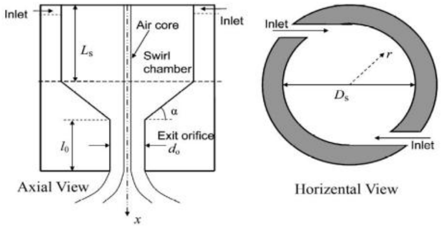


Figure1. SCHEMATIC VIEW OF SIMPLEX ATOMIZER

2. METHODOLOGY

In this study, the experimental investigation was performed to understand the effect of area of inlet tangential ports on four performance parameters such as coefficient of discharge (C_d), Spray Cone angle (θ), Sauter mean diameter of droplet (μm) and Particle size distribution for various injection pressures. Dimensions of three different small scale simplex atomizer configurations representing different inlet ports area is shown in table – 1. Figure – 2 shows cross sectional view of swirl chamber of the three different configurations. Water was used as a medium to characterize the atomizer. Atomizer constant (K) is defined as ratio of total port area to product of swirl chamber diameter and orifice diameter. Atomizer constant value of three different configurations chosen for present study also mentioned in table – 1.

Variables	Case –1 (0.7X2X0.9)	Case – 2 (0.9X3X0.9)	Case – 3 (1X4X0.9)
d_o (mm)	0.9	0.9	0.9
l_o (mm)	0.5	0.5	0.5
D_s (mm)	4	4	4
L_s (mm)	8	8	8
N_p	2	3	4
D_p (mm)	0.7	0.9	1
K ($=A_p/D_s*d_o$)	0.2138	0.5301	0.8726

The dimensional details of three configurations used are shown in table-1.

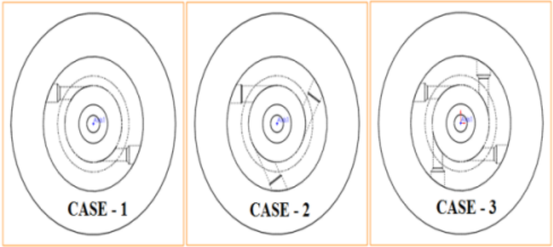


Figure 2. SWIRL CHAMBERS OF THREE DIFFERENT CONFIGURATIONS OF SIMPLEX ATOMIZER

The cone angle of the spray was measured from the images of spray of water emerging from the atomizer by doing digital image processing using Matlab program. The images were taken by digital camera. A Matlab program was developed to measure distance between the edges of spray (L). These measurements were carried out at a distance of 60d$_o$ downstream of the nozzle orifice exit as shown in the figure – 4. The experimental setup used to measure cone angle is shown in figure – 5. Sauter mean diameter (SMD) is the diameter of the drop whose ratio of surface to volume is equal to that of entire spray. Droplet volume distribution is also important parameter to characterize the atomizer. SMD and DSD measurements were carried out using Malvern droplet size analyzer. These measurements were carried out at a distance of 60d$_o$ downstream of the nozzle orifice exit.

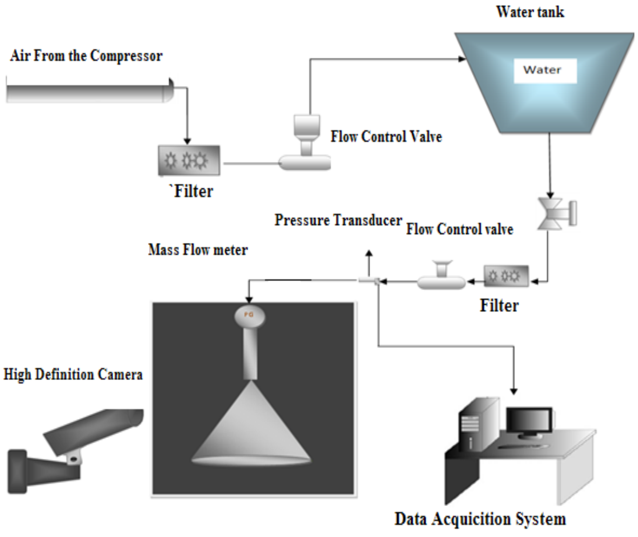


Figure 3. EXPERIMENTAL SETUP USED TO MEASURE CONE ANGLE

Malvern droplet size analyzer measures droplet size and distribution by LASER diffraction technique. This has 10mm diameter, 5mW Helium-Neon laser beam of 632.8nm wavelength. With 300mm optical lens, spray diameter from 0.1 to 900 micron sizes can be measured. A separate purge air was used to protect the optical lenses of source and receiver of Malvern droplet size analyzer from water particles during the experiment.

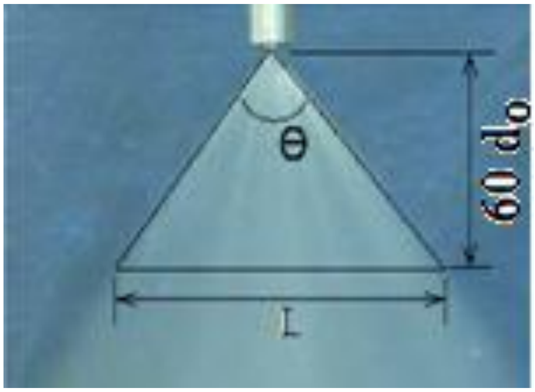


Figure 4.HOLLOW SPRAY PRODUCED BY ATOMIZER

Air from high pressure reservoir was used to pressurize the water. Water flow rate and pressure can be varied by flow control valve (FCV). Pressure was measured by transducer and mass flow rate was measured by Coriolis mass flow meter. Atomizer mounted on the traverse mechanism and water connection was given to it through mass flow meter and pressure gauge. Pressure can be increased up to 25 bar by flow control valve. After getting continuous spray as shown in figure – 2, the laser beam of Malvern spray sizing instrument was passed through water spray as shown in figure – 3 and droplets were measured by laser scattering technique. Figure – 6 shows experimental setup used for SMD and droplet size distribution measurement.

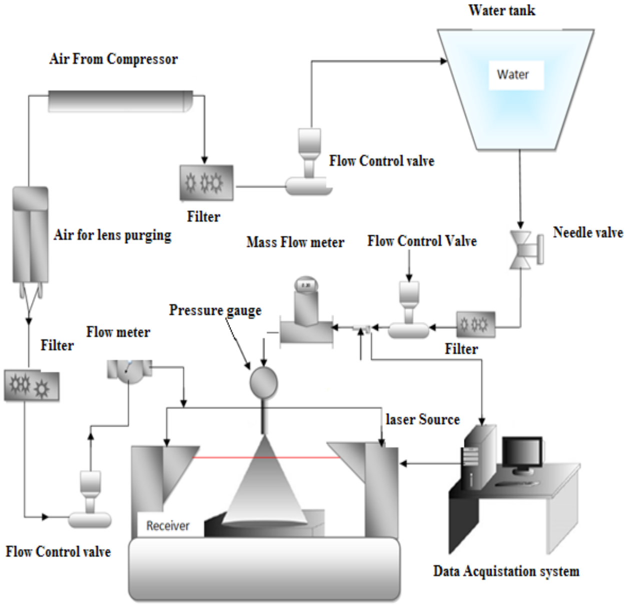


Figure 5. EXPERIMENTAL SETUP USED TO MEASURE SMD AND DROPLET SIZE DISTRIBUTION

4. RESULTS AND DISCUSSION:

4.1 Effect of port area on coefficient of discharge:

The coefficient of discharge is the ratio of the actual to the theoretical mass flow rate as mentioned in equation (1). Actual flow rate is measured by using Coriolis mass flow meter. Theoretical mass flow is evaluated using equation (2) and coefficient of discharge was measured.

$$C_d = \frac{M_a}{M_t} \qquad (1)$$

$$M_T = \rho_L A_o \sqrt{\frac{2\Delta P}{\rho_L}} \qquad (2)$$

$$C_d = \frac{\dot{M}_A}{\rho_L A_o \sqrt{\frac{2\Delta P}{\rho_L}}} \qquad (3)$$

Figure – 6 shows variation of actual mass flow rate with injection pressure of three port area configurations. As expected, mass flow rate increases with increase in presure difference.

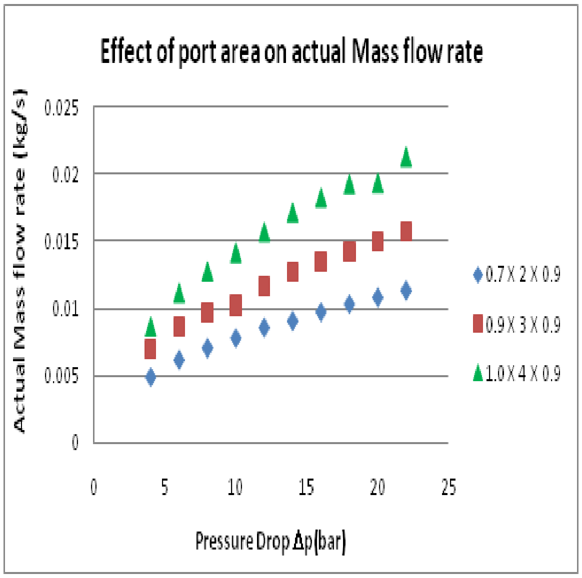


Figure 6: VARIATION OF ACTUAL MASS FLOW RATE WITH INJECTION PRESSURE OF THREE PORT AREA CONFIGURATION.

According to A.R Jones[10] the coefficient of discharge of a pressure-swirl atomizer is related to atomizer dimensions and experimental data by the equation 4

$$C_d = 0.45\left(\frac{D_o \rho_L V}{\mu_L}\right)^{-0.02}\left(\frac{L_o}{D_o}\right)^{-0.03}\left(\frac{L_s}{D_s}\right)^{0.05}\left(\frac{A_p}{d_o D_s}\right)^{0.52}\left(\frac{D_s}{D_o}\right)^{0.23} \qquad (4)$$

Rizk and Lefebvre [2], derived the following relationship is related to atomizer dimensions for C_d given equation 5:

$$C_d = 0.35\left(\frac{A_p}{D_s d_o}\right)^{0.5}\left(\frac{D_s}{d_o}\right)^{0.25} \qquad (5)$$

From the equation 4 and 5 it can be seen that the coefficient of discharge is a strong function of atomizer constant. So as the atomizer constant increases from case – 1 to case – 3 (as mentioned in table 1) the coefficient of discharge increases. The values of coefficient of discharge were plotted against injection pressure of three port area configurations in figure – 7. Also in figure – 7 the experimental values of coeficient of discharge is compared with experimental correlations of Rizk & Lefebvre and A.R Jones. The experimental values are close to the experimental correlations.

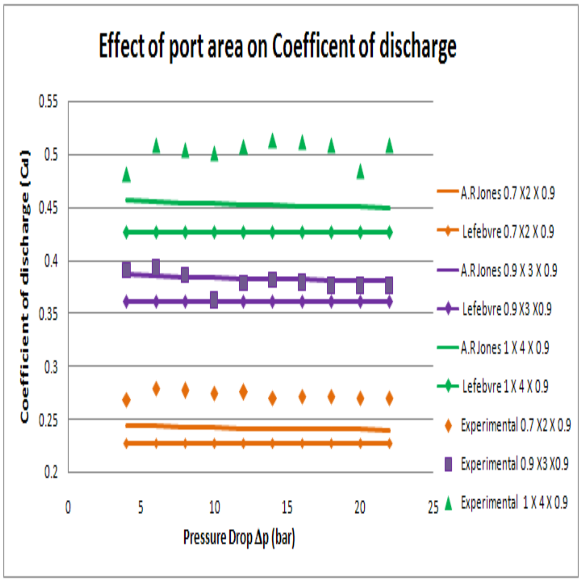
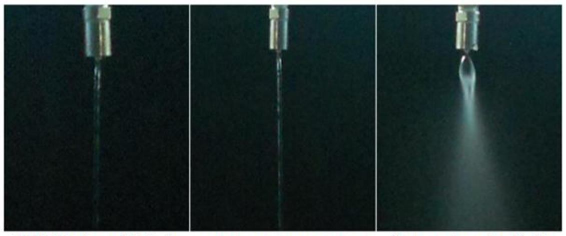


Figure 7: VARIATION OF COEFFICIENT OF DISCHARGE WITH INJECTION PRESSURE OF THREE PORT AREA CONFIGURATION.

It was observed that with increase in area of inlet tangential ports the size of air core produced along the center line reduced, which increases the sheet thickness of water spray coming from nozzle orifice. This increase in sheet thickness allows more mass flow rate, which increases coefficient of discharge. So with increase in area of inlet tangential ports the coefficient of discharge increases as shown in figure – 7, which results increase in the mass flow rate through final orifice as shown in figure – 6.

4.2 Effect of port area on Spray angle (θ):

Spray angle is defined as the full cone angle produced by spray emanating from the simplex atomizer at nozzle exit. The cone angle increases with increase in the pressure drop as shown in the figure – 8. Figure – 8 also shows the five different stages of spray with increase in injection pressure.



Dribble stage (1 Bar) **Distorted pencil (2 Bar)** **Onion stage (3 Bar)**

Tulip Stage (6 Bar) **Fully Developed cone (8 Bar)**

Figure 8: FIVE DIFFERENT STAGES OF SPRAY WITH INCREASE IN INJECTION PRESSURE.

Risk and Lefebvre [2] derived following relationship for spray cone angle θ:

$$\theta = 6K^{-0.15}\left(\frac{\Delta P_L\, d_o^2 \rho_L}{\mu_L^2}\right)^{0.11} \qquad (4)$$

Benjamin [6] validated this equation using their data base and modified the coefficients as following:

$$\theta = 9.75\left(\frac{A_P}{D_o D_s}\right)^{-0.237}\left(\frac{\Delta P D_o^2 \rho_L}{\mu_L^2}\right)^{0.067} \qquad (5)$$

To measure spray cone angle images of spray was taken from all four sides, the average was taken for analysis. In the figure – 9 spray cone angle processed by Matlab program was plotted against injection pressure for the three configurations. From the figure – 9 it can be observed that, with increase in injection pressure, cone angle initially increases up to injection pressure of 16 bar and then there is no further appreciable change. The experimental values have better match with experimental correlation provided by Rizk and Lefebvre than Benjamin. Cone angle of spray produced by lower port area configuration is higher than other two cases. Increase in inlet area of tangential ports reduces the swirl intensity inside swirler chamber, which reduces the angular velocity component of jet emanating from orifice. So higher port area configurations produces sprays with relatively smaller cone angle.

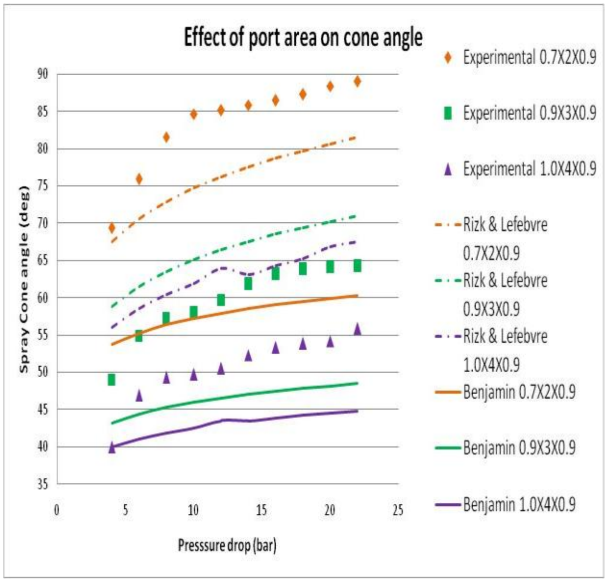


Figure 9: VARIATION OF CONE ANGLE WITH INJECTION PRESSURE OF THREE PORT AREA CONFIGURATION.

4.3 Effect of port area on Sauter mean diameter:

The SMD was measured using Malvern spray analyzer at distance of $60d_o$ downstream from orifice exit. In figure 10 measured values of SMD was plotted against injection pressure differential of three port area configurations. It was found that initially the drop size decreased rapidly with increasing pressure (4 to 12bar), but the influence of injection pressure gradually decreased at higher pressure values (14 to 22bar) as shown in figure. The experimental results are compared with experimental correlation derived by Risk and Lefebvre [2].

$$SMD = 2.25 * \sigma^{0.25} * \mu_L^{0.25} * \dot{m}_L^{0.25} * \Delta P_L^{-0.5} * \rho_A^{-0.25} \quad (6)$$

Where

$$\dot{m}_L = C_d\, \rho\, A\, V \qquad (7)$$

Sauter mean diameter of case – 1 is lower than other cases, so lower port area case is giving better atomization. Increase in inlet area of tangential ports reduces the swirl intensity inside swirler chamber, which increases thickness of sheet of spray emanating from orifice. So higher port area configurations produces sprays with relatively higher drop size. At higher injection pressures the spray produced by all the three configurations becomes highly unstable so at higher injection pressure the effect port area on the drop size is much lower than at lower injection pressure.

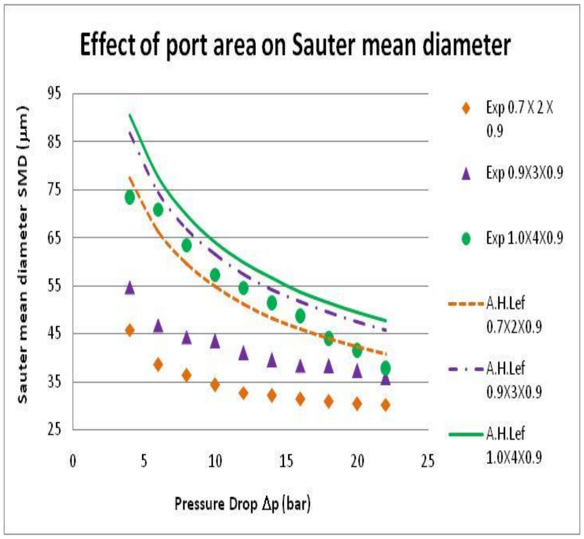


Figure 10: VARIATION OF SMDWITH INJECTION PRESSURE OF THREE PORT AREA CONFIGURATION.

4.4 Particle size distribution:

In general to verify spray behaviour of atomizers coefficient of discharge, SMD and spray cone angle were considered as performance parameters, but droplet size distribution also equally important parameter to verify spray quality. In the present study droplet size distributions were measured for all the three configurations of atomizer. The diameters of droplets were divided into three ranges 0 to 19µm, 20 to 100µm and higher than 100µm. The volume percentage each range of droplet diameter was directly obtained from statistical software of Malvern spray analyzer at five different injection pressures of three configurations. Droplets in the range of 20 – 100 µm was considered as optimum range for better combustion (without soot formation and shorter vaporization time). Figure – 11 shows droplet size distribution at five different injection pressures (4, 8, 12, 16 and 20 bar) of the three configurations. With increase in injection pressure droplets in the range of 0 – 19 µm, 20 – 100 µm increases and droplets in the range of more than 100 µm decreases. Volume percentage of droplets in the range of 20 – 100 µm is higher for case – 1 compare to other two cases at all injection pressure. At 20 bar volume percentage of droplets in the range of 20 – 100 µm is 83 % for case – 1 (0.7 X 2 X 0.9), 62 % for case – 2 (0.9 X 3 X 0.9) and 41 % for case – 3 (1.0 X 4 X 0.9). Thus lower area of inlet tangential ports improves atomization quality.

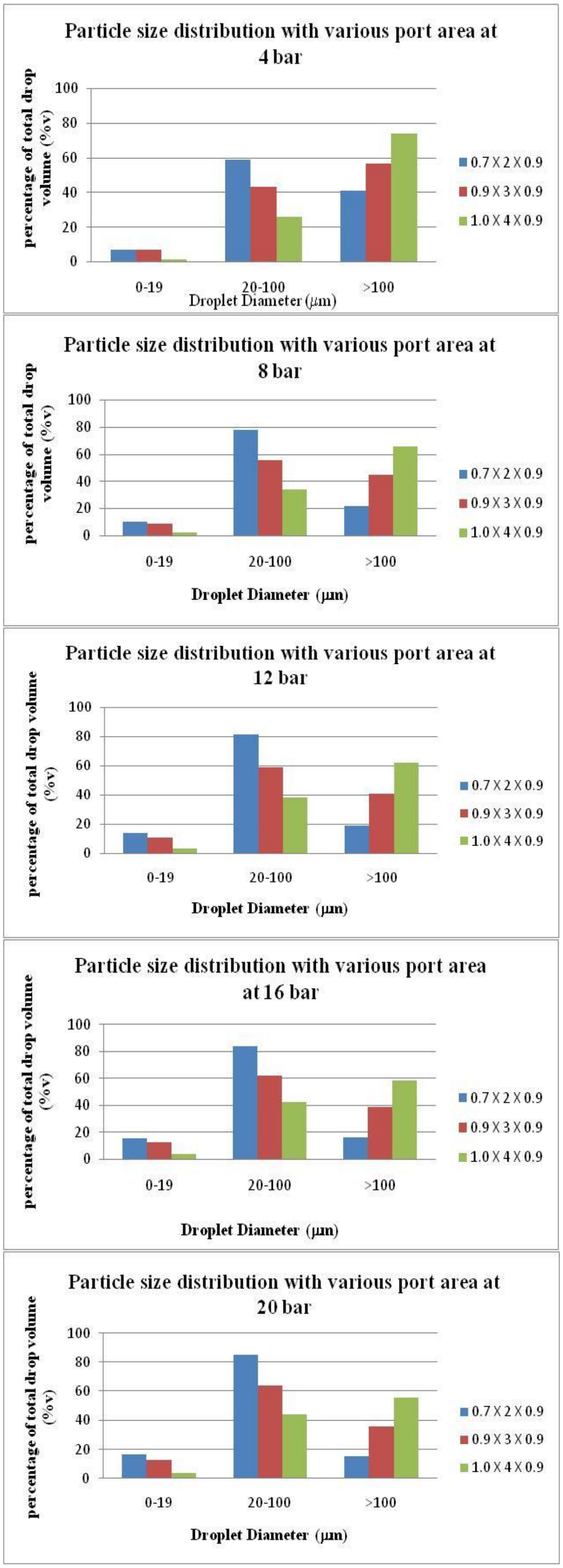


Figure 11: DROP SIZE DISTRIBUTION OF THREE PORT AREA CONFIGURATION.

5.0 CONCLUSION:

An experimental investigation was conducted to understand the effect of increased area of inlet tangential ports on the performance of spray produced by small scale simplex atomizer at different injection pressure up to 22 bar. From the experimental study following conclusions are made.

1. Increase in port area reduces the size of air core produced along the center line, which increases coefficient of discharge.
2. Increase in injection pressure does not affect the coefficient of discharge for all the three cases.
3. Increase in tangential port area reduces spray cone angle.
4. Increase in injection pressure increases the spray cone angle up to 16 bar, but after that there is no significant increase in the cone angle.
5. Increase in tangential port area reduces swirl strength inside swirl chamber, which reduce atomization quality and Sauters mean diameter.
6. At higher injection pressure effect of port area on Sauters mean diameter is lower than at lower injection pressure.
7. Volume percentage of droplets in the range of 20 – 100 µm is for lower port area configuration than other two cases at all injection pressure.

Nomenclature

l_o - Orifice length (mm)
d_o - Orifice Diameter (mm)
D_s - Swirl Chamber Diameter (mm)
L_s - Swirl Chamber Length(mm)
M_T - Theoretical mass flow rate (kg/s)
A_p - Total port area (mm^2)
N_p - Number of Ports
D_p - Diameter of Ports(mm)
ΔP_L - Injector Pressure differential (N/m^2)
M_A - Actual mass flow rate (kg/s)
ρ_L - Liquid Density (kg/m^3)
A_o - Orifice exit area (mm^2)
ρ_A - Ambient density (kg/m^3)
μ_L - Liquid dynamic viscosity ($N\text{-}s/m^2$)
SMD - Sauter mean diameter (µm)
DSD - Droplet size distribution
K - Atomizer Constant
Cd - Coefficient of discharge

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