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Effects of Flow Parameters on Spray Characteristics of a Modified Pressure Swirl Atomizer

Gad H. M.[1], Baraya E.A.[1], Farag T.M.[1], Ibrahim I.A.[1]
[1](Mechanical Power Engineering Department, Faculty of Engineering, Port Said University, Egypt)

Abstract:
In the present study, air assist and pressure swirl atomizers spray momentum and breakup length were investigated under different vales of discharge coefficients and flow numbers.
Discharge coefficient was changed from 0.19 to 0.22 by decreasing the spin chamber diameter of the examined atomizer from 14 mm to 8 mm. The flow number of a modified pressure swirl atomizer was varied from 1.56 to 2.5 by changing the atomizer constant from 0.125 to 0.3125. Spray momentum and breakup length were studied under different operating and geometrical conditions using water as atomized liquid. Spray momentum was calculated theoretically from the spray concentration and experimentally measured by specially designed device. Momentum efficiencies were presented at different flow numbers and discharge coefficients.
When the flow number increased, the momentum efficiency increased which gave an indication for soot formation in the combustion process, the spray breakup length clearly decreased. Breakup length was inversely proportional with discharge coefficient while spray momentum was directly proportional with discharge coefficient.
Key Word*:Pressure swirl; Breakup length; Spray momentum; Discharge coefficient.*

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I. Introduction

Pressure-swirl atomizers (PSA) has advantage of simple construction, low cost, requirement small amount of energy for atomization and high reliability. Pressure swirl atomizer (PSA) is consider one of the most used atomizers in combustion systems[1]. One of pressure swirl atomizer modification is using assisted air which helps to enhance spray characteristics. Kai Yan et al.[2] indicated that, smaller distribution ranges of breakup droplets are obtained at higher liquid swirling strength, higher Weber numbers. The use of assisted air with swirling effect improved the atomization from both droplet size distributions and velocity distribution. The discharge coefficient of pressure swirl atomizer affected on the pressure losses occurred in the atomizer swirling passage and spin chamber, thus atomizer internal geometry affected the discharge coefficient, as the atomizer constant (K) was directly proportional with discharge coefficient. The atomizer flow rate through discharge orifice was controlled through discharge coefficient (C_D). As the length to diameter ratio (L/D_o) of nozzle increased, the C_D increased until it reached its maximum value, it began to reduce with L/D_o increase. For fuels of low viscosity, the Reynolds number over 3000 the discharge coefficient is independent to Reynolds number[3,4,5].

Discharge coefficient of a pressure-swirl atomizer is related to atomizer dimensions and the area of the air core, which produced due to swirling motion of fuel in the spin chamber. In pressure-swirl atomizers, the thickness of this film is directly related to the area of the air core. Air core diameter is directly proportional with the swirling effect in the spin chamber[6,7]. The experimental measurement of discharge coefficient were carried out in different operating conditions of nozzles and different nozzle geometries, thus it was found to be related with Reynolds number, nozzle length/diameter ratio, injection pressure, spin chamber geometry, type of swirl nozzle (open or closed) and inlet chamfer[8]. Flow number of discharge nozzle was considered the primary source of the combustion noise. The flow number is constant value for certain atomizer for all liquids, thus the flow number variation is a function in atomizer geometry as indicated by Lefebvre and McDonell[3]. The assisted air pressure swirl atomizer (AAPSA) geometry can concluded in the nozzle constant (K) (ratio of total inlet area to product of the swirl chamber and orifice diameter) which is the main parameter affecting the nozzle performance.

$$K = A_p/(D_s \cdot D_o) \quad (1)$$

Where Ap is the total area of tangential entry ports in mm^2, D_s is the spin chamber diameter in mm and D_o is the orifice diameter in mm. Flow number of air assist pressure swirl atomizer are strongly affecting the spray characteristics such as droplet size distribution[3,9]. Lefebvre and McDonell[3] presented an empirical relation of flow number (FN) with the film thickness (t) of hollow cone spray and spray cone angle (θ).

$$t = (0.00805\ SQRT(\rho_L).\ FN)/(D_o\ .\ \cos\theta) \qquad (2)$$

where ρ_L is the liquid density in kg/m^3.

In combustion systems, the fuel spray momentum is a very important parameter because it effects on the spray penetration inside the combustion chamber and spray cone angle, indicates the mixture distribution and controls the condensation due to impinging with the surfaces inside the combustion chambers. Ibrahim et al.[10] investigated and measured the spray momentum by directing the fuel spray onto a fixed plate connected with a force sensor to measure the force of the spray impact on the plate. The reliable atomizer that should minimizes soot formation to be minimum, which maximizes the axial momentum from the spray hole for a given fuel injection pressure and fuel mass flow. To be able to check the axial momentum of the atomizer a new parameter was introduced by Godfrey et al.[11] named atomizer momentum efficiency (η_m), it defined as the ratio of actual momentum flux measured for atomizer spray to the theoretical momentum flux calculated from the mass flow rate at each injection pressure.

$$\eta_m = M_{act}/M_{th} = (\dot{m}U_{act})/\ (\dot{m}U_{th}) = U_{act}/U_{th} = M_{act}/\ (\dot{m}SQRT(2\Delta P\rho_L) \qquad (3)$$

where, M_{act}, M_{th} are the actual and theoretical spray momentum, respectively, $\dot{m}$ is the mass flow rate of spray, U_{act} and U_{th} are the actual and theoretical velocities of spray droplets, respectively, ΔP is the pressure difference.

The common purpose of breaking a bulk liquid jet into spray is to increase the liquid surface area and decreasing the breakup length to minimum value so that subsequent heat and mass transfer can be increased[12, 13, 14, 15]. The breakup length (L_b) is measured by different methods such as optical connectivity, electrical connectivity and shadowgraph techniques. The maximum error found between different techniques was within ±15%. The breakup length is defined as the length from the spray nozzle to the end of continuous spray sheet[15, 16, 17].

From the previous review, it showed the importance of studying the effects of discharge coefficient and flow number in the breakup length and droplet spray momentum. AAPSA momentum efficiency at different flow numbers and discharge coefficients to show the more effective parameter that affect the spray momentum. Many researchers study the effects of discharge coefficient and flow number on performance of pressure swirl atomizer, while in the present work, the study after using assisted air with pressure swirl atomizers will be presented. The design of modified pressure swirl atomizer will be introduced to overcome the orifice limitation problem; liquid disintegration occurs through annulus orifice as mentioned by Ibrahim et al.[10]. The effects of changing the flow number and discharge coefficient for different AAPSA and PSA on the breakup length and spray momentum will be investigated. Geometrical parameters of AAPSA and PSA were changed to make the desired change in flow number and discharge coefficient.

II. Experimental Test Rig

The spray momentum distribution is measured using experimental apparatus which using sensing force sensor to measure spray droplet force in gram force. The measuring force sensor can measure the momentum in different radial positions of spray at specific distance form atomizer nozzle. In the present work, the spray momentum is studied under different geometrical parameters using force sensing resistors (FSR), as shown in Fig. 1 which illustrates the spray momentum measuring arrangement. A polymer thick film (PTF) device is used in the spray momentum measurement. Figure 2 shows the detailed dimensions of the air assist pressure swirl atomizer, the modified atomizer consists of main five parts; (1) atomizer body, (2) locking part to swirl fuel passage, (3) swirling part of fuel with different angles, (4) atomizer cap with different orifice diameters which contains spin chamber with cylindrical geometry and (5) central air needle. Theoretical calculations of spray momentum are presented under different geometrical parameters and calculated using the results from spray concentration distribution (SCD). The flow velocity of each tube of the spray patternator is calculated using the discharge collected in each tube and the cross-sectional area of the tube. Spray concentration distribution is measured using an inline patternator consists of 23 tubes 12 mm diameter each. Patternator located at a specified constant vertical distance of 22 cm from the atomizer exit to achieve the full envelope diameter of the spray.

Measurements are carried out at atmospheric temperature of 27°C. The maximum error with nominal flow rate is found to be about ± 3.5%.

The breakup measurements are carried out using different methods as previously presented[12, 18]. In the present study, the breakup length is measured with simple electrical circuit consist of two electrodes; first one is the copper atomizer body and the second is copper link which contacts the spray from the atomizer. The electrical measuring circuit as shown in Fig. 3 consists of (1) Dc voltage source, (2) Dc 12 voltage buzzer, (3) lamp, (4) 10 kΩ electrical resistant, (5) atomizer (first electrode) and (6) copper link (second electrode). Dc 12 voltage buzzer connected parallel to 10 kΩ electrical resistant and led lamp. The continuous liquid represents the switch of the circuit which closes the electrical circuit.

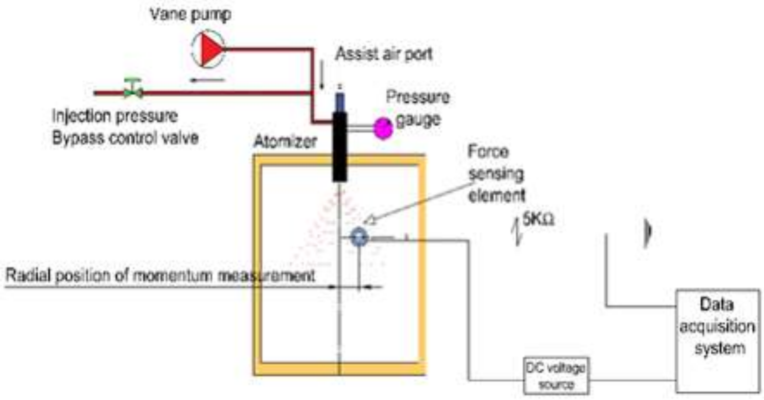

Fig. 1 Schematic diagram of momentum the test rig

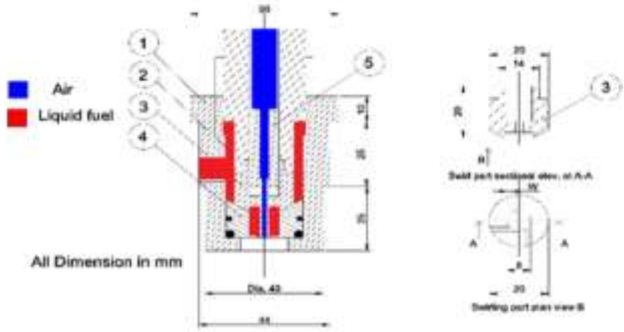

Fig. 2 Detailed dimensions of the air assisted pressure swirl atomizer

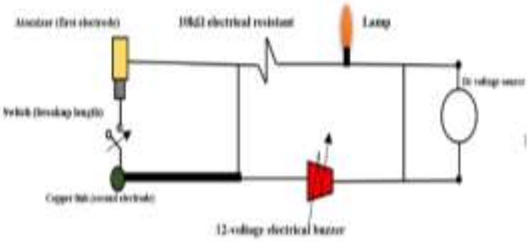

Fig. 3 Breakup length electrical DC circuit

III. Results and Discussion

In this section, a series of experiments are carried out to investigate the effects of changing the values of flow number (FN) and discharge coefficient (C_D) of air assist pressure swirl atomizer (AAPSA) and pressure swirl atomizer (PSA) on the breakup length (L_b), droplet spray momentum and the AAPSA momentum efficiency.

3.1 Breakup length (L_b)

Jet breakup phenomenon of spray jet are affected by four important forces, inertia force, viscous force, surface tension and aerodynamic forces acting on the jet[10, 16]. Surface tension is physical property that resists expansion of liquid surface area. Surface tension forces must be overcome by aerodynamic, centrifugal or pressure forces to achieve proper atomization. The common purpose of breaking a bulk liquid jet into spray is to increase the liquid surface area and decreasing the breakup length to minimum value so that subsequent heat and mass transfer can be increased. The breakup length measured by other experimental technique previously studied[13, 19] with uncertainty of about ± 4%. The effective flow area of a pressure atomizer is usually described in terms of flow number, which is expressed as the ratio of the nozzle throughput to the square root of the fuel-injection pressure differential[1,3]. Flow number of a pressure swirl atomizer is obtained in terms of atomizer dimensions as in the following equation:

$$FN = 0.389\,(D_o)^{1.25}\,(A_p)^{0.5}(D_s)^{-0.5} \quad (4)$$

In the present study, the flow number is changed from 1.56 to 2.5 by changing the area A_p with the variation of swirl ports size, the area A_p is changed from 5 to 12.5 mm^2. Figure 4 shows the effect of flow number on the breakup length (L_b) at different injection pressures at D_o/L_o= 0.27, L_s/D_s= 0.93 and Ø = 90°, where L_o, L_s are the lengths of the discharge orifice and spin chamber, respectively and Ø is fuel swirl angle in degree. The three parameters that influence the flow number of the AAPSA is the spin chamber diameter, width and depth of swirl ports and orifice diameter. The desired change of the flow number is by changing wet area of swirl ports. When the flow number increased from 1.56 to 2.5 the spray breakup length decreased by about 36, 38 and100% at injection pressures of 1, 3 and 6 bar, respectively for PSA while it decreased by about 42, 40 and 100% at injection pressures of 1, 3 and 6 bar, respectively for AAPSA. Increasing mass flow rate of atomizing liquid leads to increase the value of flow number and low discharge coefficient, therefore helps to more disintegration of atomizing liquids in small droplets reducing of continuous liquid length from atomizer nozzle. The percentage of breakup lengths are more in cases of AAPSA than in PSA due to effect of assisted air which acts as excessive atomization of bulk liquid.

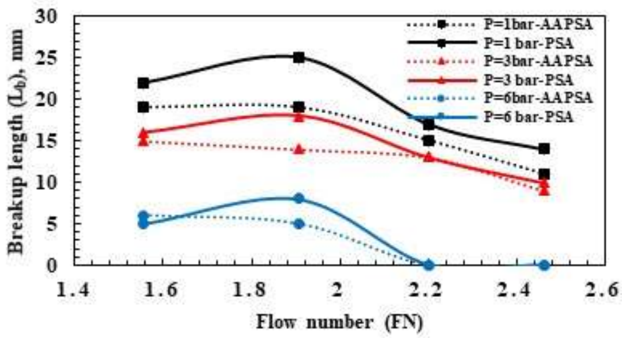

Fig. 4 Effect of flow number on the breakup length at different injection pressures [D_o/L_o=0.27, L_s/D_s=0.93 and Ø = 90°]

The discharge coefficient of a swirl atomizer is low due to the presence of the air core which effectively blocks off the central portion of the orifice[1, 20]. The discharge coefficient of a pressure swirl atomizer is related to atomizer dimensions and the area of the air core by the equations described by Gao et al.[5].

$$C_D = 1.17[(1-X)^3/(1+X)]^{0.5} \quad (5)$$

where X = (Air core area)/(Discharge orifice area), X is calculating from relationship between atomizer dimension and air core size.

$$[A_p/(D_s\,D_o)]^2 = (\pi^2/32)(1-X)^3/X^2 \qquad (6)$$

The following relationship, which is based on the analysis of a large amount of experimental data by Lefebvre[3].

$$C_D = 0.36(K)^{0.5}(D_s/D_o)^{0.25} \quad (7)$$

where K is nozzle constant and previously described. The discharge coefficient increased with increasing atomizer constant K, spin chamber diameter and decreasing of discharge orifice diameter.

Using the discharge coefficient, the spray angle and the liquid film thickness of AAPSA can be estimated to provide the characteristics of liquid droplets as discussed by many researchers[20, 21]. The discharge coefficient can be finally calculated from equation (7). Figure 5 shows the effect of discharge coefficient on the breakup length at different injection pressures at D_o/L_o = 0.27, WxH = 1.5x1.5 and Ø = 90°, where W and H are the swirl passage width and depth, respectively in mm. It is appeared that breakup length decreased as the discharge coefficient increased. As the discharge coefficient increased from 0.189 to 0.22 the spray breakup length decreased by about 65, 68 and 100% at injection pressures of 1, 3 and 6 bar, respectively for PSA and by about 73, 90 and 100% at injection pressures of 1, 3 and 6 bar, respectively for AAPSA. It is known that; breakup length is inversely proportional with atomizer constant and many researchers have agreed with this such as Ibrahim et al.[10]. The effect of the atomizer constant (K) is the key factor of variation of discharge coefficient. As the atomizer constant increased, the discharge coefficient increased. This explains the increase in breakup length with discharge coefficient. According to equation (7), the discharge coefficient is depending on the nozzle constant (K) and the spin chamber diameter and discharge orifice diameter does not depend on the injection pressure.

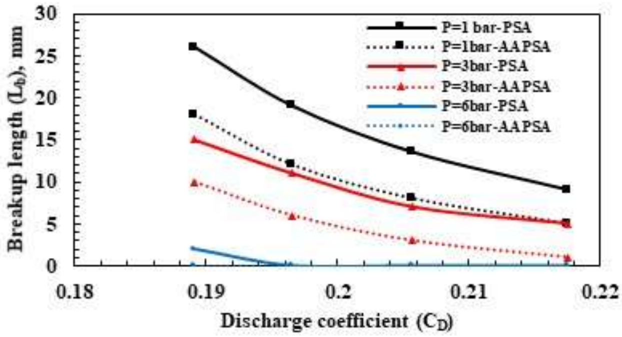

Fig. 5 Effect of discharge coefficient on the breakup length at different injection pressures [D_o/L_o=0.27, WxH=1.5x1.5 and Ø = 90°]

3.2 Spray momentum

Spray momentum can be measured by directing the fuel spray onto a fixed plate that is arranged to measure the impact force on the plate necessary to destroy all the axial momentum in the fuel spray/jet[10, 22, 23]. The spray momentum is an important factor, which indicates the penetration of the spray inside the combustion chamber. Spray momentum plays significate role in mixing and air fuel ratio, therefore affects soot formation in combustion process. The spray momentum can be investigated to increase its penetration to get good mixing with combustion air and avoid impingement onto combustor walls. Due to symmetrical radial distribution of spray momentum, half of the spray envelops are presented. In the present work, the spray momentum is studied under different geometrical parameters and calculated using the results from spray concentration distribution as previously presented[10, 22]. From the volume flow rate of each tube and the ratio between each tube area and its corresponding ring area, the volume flow rate δQ of each ring in (cm^3/s) is calculated. The spray momentum δM can be determined for each ring as following:

$$\delta M = \delta \dot{m} \cdot V \qquad (8)$$
$$\delta \dot{m} = \delta Q \cdot \rho_L \qquad (9)$$
$$V = \delta Q / A_{ring} \qquad (10)$$

where δM is the spray momentum in certain section, $\delta\dot{m}$, δQ and V are spray mass flow rate, discharge and velocity through the section of area A_{ring}. Theoretical calculation of spray momentum is investigated under different geometrical parameters and calculated using the results from radial spray concentration. The flow velocity of each tube is calculated by indicating the cross-section area of single tube from the collected liquid in each. Figure 6 shows the effect of changing radial position on measured and calculated spray momentum of AAPSA at 2 g/s, P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25 which indicates the measured and calculated spray momentums. The maximum error between the measured and calculated spray momentums is about 20%. Therefore, the patternation technique in calculation of spray momentum gave an indication or trend to spray momentum but not accurate method in indicate of spray momentum.

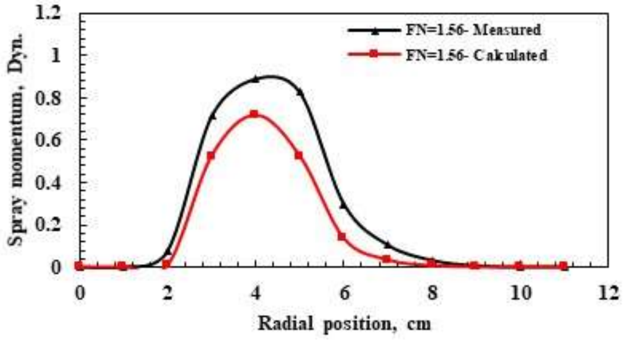

Fig. 6 Radial distribution of measured and calculated spray momentums of AAPSA with 2 g/s [P = 4 bar, L_s/D_s = 0.775, FN=1.56 and L/D_o = 0.25]

The flow number of AAPSA at different nozzles of atomizer make effective variation on the droplet spray momentum, which effects the impingement of spray in the combustor and soot formation in the combustion process. Figure 8 shows the radial distribution of calculated spray momentum for different values of FN for AAPSA with 2 g/s, P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25. The spray momentum has its maximum value at flow number of 2.2 at radial position of 4 cm from the spray centerline. It is noticed that the spray momentums at FN= 1.56, FN=2.5 are proximally at the same value at different radial positions of 4 cm and 5 cm, respectively. The variation of spray momentum due to flow number change caused by spray cone angle variation of each nozzle at same operating pressure. Spray momentum reduced by about 24% as FN reduced from 2.2 to 2.5 because of effective change in SCA and spray film thickness.

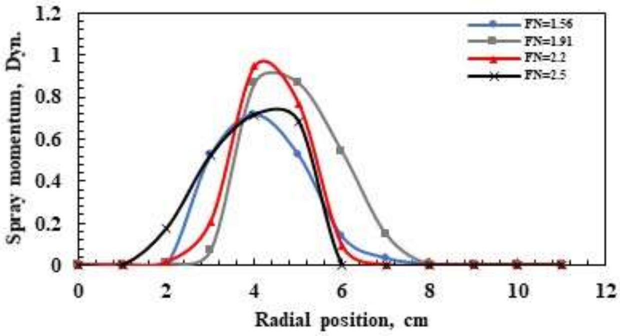

Fig. 7 Radial distribution of calculated spray momentum at different values of FN of AAPSA with of 2 g/s [P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25]

Figure 8 shows the radial distribution of measured spray momentum at different values of FN of AAPSA with 2 g/s, P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25. it is observed that the peak value of maximum momentum is changed as a result of changing the spray cone angle with different flow numbers. The peak value of spray momentum occurred at FN= 1.91, the film thickness of hollow cone spray is responsible for the peak value of spray droplet momentum. As large film thickness produced heavy droplet impingement and using of assisted air increased the pulsation of spray droplet after disintegration.

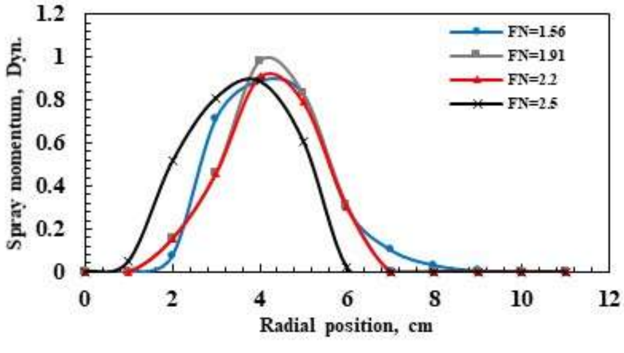

Fig. 8 Radial distribution of measured spray momentum at different values of FN of AAPSA with 2 g/s [P = 4 bar, Ls/Ds = 0.775 and L/Do = 0.25]

Momentum efficiency is considered an important parameter in combustion process. The momentum nozzle efficiency gives a good indication of combustion soot formation. Figure 9 presents the radial distribution of the momentum efficiency at different values of FN of AAPSA with 2 g/s, P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25. It is shown that increasing the flow number enhanced the atomizer momentum efficiency, the efficiency increased by about 43% as the flow number increased from FN= 1.56 to FN=2.5. The increased of flow number due to swirl area which increased A_p, therefore as swirl area of AAPSA increased this helps to increase the film thickness of spray pattern due to reduction in spray cone angle of developed spray.

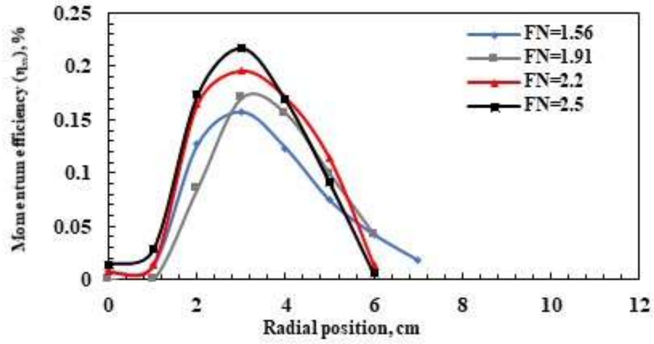

Fig. 9 Radial distribution of spray momentum efficiency at different values of FN of AAPSA with 2 g/s [P = 4 bar, L_s/D_s = 0.775 and L/D_o = 0.25]

Discharge coefficient (C_D) is important parameter, which affects the spray characteristics of PSA and AAPSA. Discharge coefficient play an important role in variation of droplet spray momentum, as atomizer internal geometry such as atomizer constant affects the discharge coefficient of atomizer[20, 21, 22]. Figure 10 illustrates the radial distribution of calculated spray momentum at different values of CD of AAPSA with 2 g/s at P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25. It is appeared that, the maximum spray momentum changes its radial position from spray center. As the discharge coefficient increased from C_D= 0.19 to 0.22, the peak value of spray momentum shifted radially toward the spray center by about 75% from its first position. Peak value of spray momentum occurred at C_D = 0.19 lower value of discharge coefficient. Figure 11 shows the radial distribution of measured spray momentum at different values of C_D of AAPSA with 2 g/s, P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25. It is shown that, the spray momentum is directly proportional with discharge coefficient. When the C_D changed from 0.22 to 0.19 the peak spray momentum is decreased by about 25%. The variation in radial position of peak spray momentum are due to spray cone angle variation with change of C_D because of atomizer constant (K) variation. The radial position of peak momentum is shifted outward from spray centerline by about 50 % as C_D increased from 0.22 to 0.19. by increasing the discharge coefficient, the peak value of spray momentum increased and shifted radially inward.

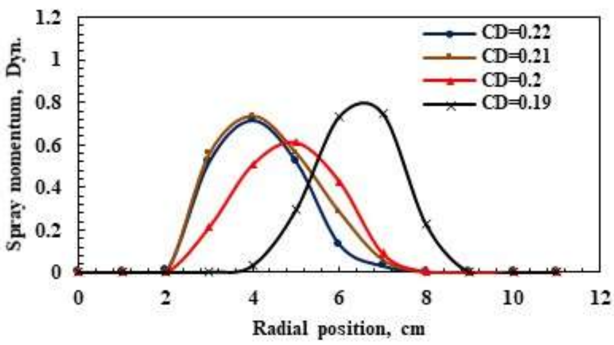

Fig. 10 Radial distribution of calculated spray momentum at different values of C_D of AAPSA with 2 g/s [P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25]

The radial distribution of momentum efficiency at different values of C_D of AAPSA with 2 g/s, P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25 is shown in Fig. 12. The momentum efficiency increased as the discharge coefficient increased as a result of increase of atomizer constant (K). As the discharge coefficient reduced from 0.22 to 0.19 the momentum efficiency reduced by about 35%. The radial position of the peak momentum efficiency is changed due to large variation of spray cone angle with atomizer constant variation (K). The peak momentum efficiency decreased and shifted radially outward by decreasing the discharge coefficient. As

$C_D$reduced from 0.22 to 0.19 the peak value of ηm shifted outward from 4 cm to 7 cm from spray centerline, thus percentage variation in radial position as C_D varied from 0.22 to 0.19 is by about 75%.

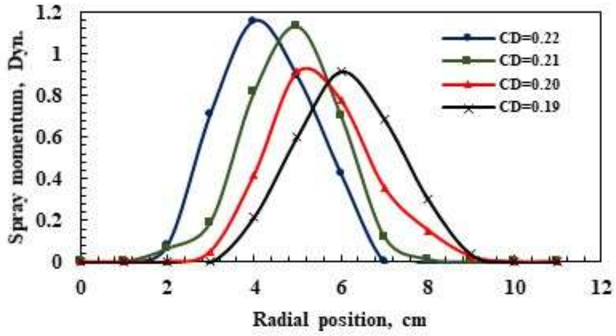

Fig. 11 Radial distribution of measured spray momentum at different values of C_D of AAPSA with 2 g/s [P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25]

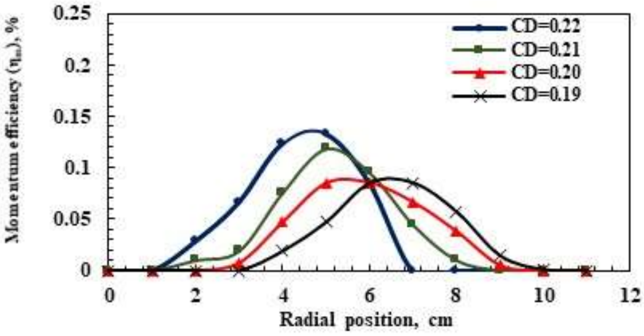

Fig. 12 Radial distribution of momentum efficiency at different values of C_D of AAPSA with 2 g/s [P = 9 bar, WxH=1.5x1.5 and L/D_o = 0.25]

IV. Conclusion

From the experimental results, the following conclusions can be summarized:

- Patternation technique in calculation of spray momentum gave an indication or trend to spray momentum but not accurate method in indicate of spray momentum.
- Spray momentum percentage error is about 20% between measured and calculated.
- As flow number increased from 1.56 to 2.5 spray breakup length decreased by 36%, 37.5%, 100% at injection pressures of 1, 3 and 6 bar, respectively for PSA.
- As flow number increased from 1.56 to 2.5 spray breakup length decreased by 42%, 40%, 100% at injection pressures of 1, 3 and 6 bar, respectively for AAPSA.
- Breakup length inversely proportional with atomizer discharge coefficient.
- Spray momentum reduced by about 24% as FN increased from 2.2 to 2.5.
- The increase of flow number improved momentum atomizer efficiency and the efficiency increased by about 43% as the flow number increased from 1.56 to 2.5.
- Spray momentum directly proportional with discharge coefficient. As the C_D decreased from 0.22 to 0.19 the peak spray momentum decreased by about 25%.
- The momentum efficiency increased as the discharge coefficient increased. As the discharge coefficient reduced from 0.22 to 0.19 the momentum efficiency reduced by about 35%.

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