NUMERICAL INVESTIGATION ON DIVERGENT SECTION IN ORIFICE OF PRESSURE SWIRL ATOMIZER

[1]Omkar A. Yadav,[2]Sudhakar S. Umale,[3]Ashish Vajir

[1]M. Tech Scholar,[2]Associate Professor,[3]Chief Technical officer
[1] Department of Mechanical Engineering,
[1]Sardar Patel College of Engineering, Mumbai, India.

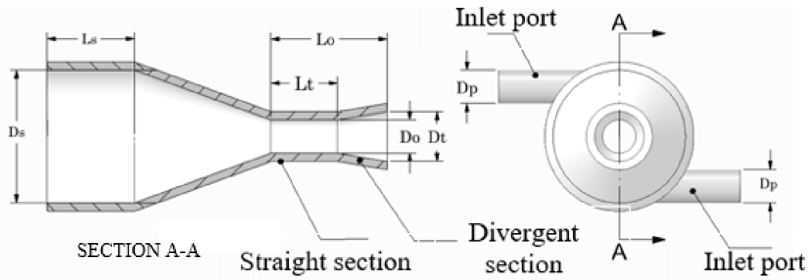
Abstract:An orifice of pressure swirl atomizer has direct effect on its internal parameters. It is generally straight and in some cases and has a diverging section to control the spray angle. A 2-D laminar, unsteady, Volume of Fluid (VOF) model is used to numerically determine the flow parameters inside the pressure swirl atomizer. Numerical investigations were conducted on this validated model by replacing the straight section in the orifice to understand its effect onkey internal parameters such as non-dimensional liquid film thickness t^*, coefficient of discharge Cd and spray angle ψ. The effect is investigated for a constant mass flow rate and the fluid chosen for atomization is water. The liquid film thickness is calculated graphically by taking volume fraction iso-surface of 0.5 and spray angle by considering the velocity distributions in the liquid sheet at the orifice exit. Non-dimensional thickness $t_{f,}$ was used to define the liquid sheet thickness exiting the orifice with reference to the orifice exit diameter. It was observed that Cd and ψ decrease when straight section of orifice was replaced by a diverging one. The value of t_f increased due to increase in the axial velocity at the orifice exit. Maximum coefficient of discharge was achieved when, a single divergent section was used in place of combination of straight and divergent in orifice having same inlet and outlet diameters. Furthermore, when the length of the straight section L, was 0.33 times that of divergent sectionLt, the atomizer produced the lowest spray angle and non-dimensional thickness. The spray angle and non-dimensional thickness were observed to be increasing monotonically with the increase in L/Ltratio.

***IndexTerms* -** Atomizer, Air core, Coefficient of discharge, Spray cone angle.

I. Introduction

Pressure swirl atomizers are used in diverse set of applications ranging from complex Pressurized Water Reactors (PWR), Boiling Water Reactors (BWR) to simple spraying of water for agricultural purposes. They can be used for condensation in De-super heaters as well as for combustion applications in diesel engines. The main elements of the atomizer as shown in Fig.1.1 are inlet ports and swirl chamber having diameter D_p and D_s respectively, convergent section which connects swirl chamber to the exit orifice of diameter D_o. The fluid comes into the swirl chamber from the tangential ports. This imparts a swirling motion to it. The convergent section increases the axial velocity and it finally leaves from the exit orifice. In many applications to control the spray angle a divergent section is added. A hollow conical liquid sheet forms at the outlet which breaks up in to droplets as a consequence of unstable nature of the liquid sheet interacting with the surrounding fluid. The droplets generated from the atomizer do not depend upon its orifice diameter but on the inlet mass flow rate. Thus the size of droplets is independent of orifice diameter, this makes it easier to manufacture compared to other types of atomizers as manufacturing of small precise holes is often complicated[1]

In contrast to the construction and working of the pressure swirl atomizer, its internal flow mechanics are very complicated. This is due to the high swirling flow of the entering fluid and the formation of air core in the opposite direction to the flow of fluid as shown in Fig.1.2. The liquid swirls inside the atomizer body with a high velocity, this creates a region of low pressure around the axis. When the pressure drops below the atmospheric pressure, the surrounding air gets sucked in. This air then travels up to the base of the swirl chamber. The column of air in between the swirling fluid is called an air core [1]. It is a very important parameter for atomization and directly controls the liquid sheet thickness. A higher degree of atomization is achieved if air core diameter, d_a increases. The coefficient of discharge, Cd is very low as a consequence of air core formation. The spray angle is also an important parameter of atomization. It determines the width or spread of the spray. The range of spray angle required depends upon the type of application. Maximum spray angle is not always desired, applications such as spraying in De-superheater pipes, gas turbines warrant a specific spray angle rather than the maximum possible range.



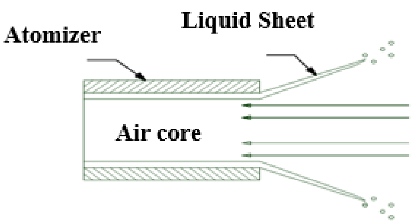


Fig.1.1.Schematic diagram of atomizerFig.1.2.Air core in the atomizer

Spray angle depends upon the strength of the swirling and axial component of the flow at the orifice exit.It is calculated by the formula shown in Eq.1.1.

(1.1)

Nomenclature

A_p	Cross sectional area of inlet ports,(mm^2)	u	Velocity in x direction (m/s)
c	Volume fraction of liquid phase	V_r	Velocity in radial direction (m/s)
C_d	Coefficient of discharge	V_z	Velocity in axial direction (m/s)
d_a	Air core diameter, (mm)	V_θ	Velocity in angular coordinate (m/s)
d_{a1}	Air core diameter at orifice entry, (mm)		Greek symbols
d_{a2}	Air core diameter at orifice exit, (mm)	α	Scalar phase volume fraction
D_o	Orifice diameter, (mm)	β	Convergent section angle in pressure swirl atomizer
D	Dimension	μ	Mean viscosity,(Pa-sec)
D_p	Diameter of inlet ports, (mm)	μ_1	Viscosity for primary phase , (Pa-sec)
D_s	Diameter of swirl chamber, (mm)	v_{eff}	Effective kinematic viscosity, (m^2/s)
K	Atomizer constant	ρ	Mean density, (kg/m^3)
L_o	Length of orifice, (mm)	ρ_1	Density for primary phase, (kg/m^3)
L_s	Length of swirl chamber, (mm)		
Lt	Length of divergent section, (mm)		Abbreviations
L_o	Length of orifice section, (mm)	BWR	Boiling Water Reactor
P	Pressure, (Pa)	CFD	Computational Fluid Dynamics
r	Radius, (mm)	FN	Nozzle Flow Number
t	time (sec)	PWR	Pressurized Water Reactor
t_f	Liquid sheet thickness (mm)	PISO	Pressure Implicit with Splitting of Operator
t*	Non- dimensional liquid film thickness	PRESTO	Pressure Staggering Option
		VOF	Volume of Fluid

II. Literature Review

Taylor [2]proposed a theory based on the assumption of frictionless flow .This theory was able to predict analytically the relation between the geometric parameters and internal flow characteristics Cd and ψ. Taylor [3] further observed that the boundary layer region near the walls cannot be assumed as in-viscid. Moreover, bulk of the liquid away from the walls has an irrotational flow behavior. Giffen and Muraszew [4] imposed a spiral motion on the free vortex to analytically get the liquid flow pattern inside the atomizer. The theory though based on simplex atomizers could be applied to duplex, spill-return type of atomizers. An expression for Cd in terms of air core diameter was derived. The variation of Cd with atomizer constant K was calculated. Where K is the ratio of area of inlet ports Ap to the product of orifice and swirl chamber diameters. K=Ap/ ($D_s d_o$) .Radcliffe [5] observed experimentally that beyond Reynolds number, Re=3000, Cd becomes independent of Re. This observation was based on wide range of atomizers involving fluids of different viscosities and densities. Most of the atomizers used in industrial application work well and above Re=3000, therefore it is a norm to disregard the effect of Re on Cd. Dombrowski and Hasan [6]in their experimental work observed that the theory proposed by Taylor [3]was able to reasonably predict the values of Cd and ψ for low viscosity fluids. Carlisle [7] proposed that value of Ds/Do should be kept below 5, whereas Tiper and Wilson [8] suggested a value of 2.5 to limit the frictional losses inside the pressure swirl atomizer. The frictional losses were directly related to Cd and as the swirl chamber diameter increased the value of Cd also increased.Joyce [9] studied the effect of different manufacturing faults occurring in production of atomizers on their performance. The general effect of various defects was to reduce the value of Cd. Jones [10] experimentally studied the effect of geometric, material and operating parameters on Cd. A large scale, three piece atomizer was specifically designed. Various dimensionless groups based on atomizer dimensions, material properties were investigated to understand their effect on Cd. An empirical relation with suitable constants was proposed. This relation indicated that material properties had very weak effect on Cd and they had an inverse relation with it. The atomizer constant K, followed by D_s/D_o ratio had a greater impact on Cd compared to other non-dimensionless groups. Jasuja [11] performed experimentations on atomizers with different orifice diameters, D_o. Crude oils and residual fuel oils were used for atomization. It was reported that the spray angle had directly proportional relationship with D_o.Rizk and Lefebvre [12] conducted experiments on simplex atomizers to investigate the effect of atomizer constant K on spray angle. Inverse and direct relation of spray angle with A_p and D_s was observed in their experimentations. It was noted that as area of inlet ports A_p decreased, the spray angle increased. This was due to the increase in swirling strength of the fluid which causes a centrifugal action on the liquid sheet making it expand. The effect of D_s was to reduce the spray angle.Lefebvre [13] observed that mean drop size of the spray is directly affected by the thickness of the liquid sheet t_f,at the orifice exit. The atomization of liquid improved as the air core diameter d_a increased and liquid sheet thickness decreased. Simmons and Harding [14] in their nozzle spray analysis derived an expression for t_f devoid of liquid viscosity and injection pressure. Only dimensional parameters were used to express t_f.Rizk and Lefebvre [15] theoretically studied the effect of geometric parameters on d_a and t_f. An expression was proposed for t_f with fluid viscosity and injection pressure. Viscosity was noted to be directly proportional to the liquid sheet thickness whereas injection pressure had an inverse relation with t_f. Nozzle flow number FN, used for calibrating of fluids in atomizer was also used in the expression. FN had directly proportional relationship with t_f. Kutty et.al.[16] performed experimentations to directly measure the air core diameter. Aninnovative photographic technique was used to capture the images of air core swirling inside a pressure swirl atomizer. A transparent swirl chamber base was used for illumination of the atomizer. Investigation was done to determine the effect of differential pressure on the air core topology.Suyari and Lefebvre [17] conducted experiments to measure the effect of inlet port diameter d_p on t_f. The measurement was done with the help of electric conductance principle. Electrodes were inserted in the discharge orifice and their conductance was used to measure the air core diameter. It was observed that for low injection pressures t_f decreases monotonically.

The difficulty in measurement of d_a and $t_f$experimentally lead to the rise of CFD techniques for determining the internal flow field of pressure swirl atomizer. The tracking of interface between the fluids is a great challenge as it is not known initially and must be solved as a part of the solution. Dash et.al[18] used Volume of Fluid (VOF) method to demonstrate air core formation in conical and cylindrical nozzle. It was observed that 2D, axisymmetric, laminar model was able to accurately predict the air core for conical nozzles. The VOF method is easier to execute and is therefore available in commercially available codes.Ma [19] conducted experiments on scaled up models of the pressure swirl atomizer to find out the velocity distribution inside the atomizer at different conditions. An axisymmetric flow was observed in the atomizer. Hansen et.al.[20] conducted simulations on a 3-D numerical model and observed that laminar VOF model was able to predict the air core formation accurately than turbulent models.

The effects of replacing divergent section in the pressure swirl atomizer are found to be lacking in the literature. In this paper, the effect of replacing straight section in the orifice of pressure swirl atomizer with a divergent section on the internal flow characteristics was investigated. The internal flow characteristics investigated were spray angle ψ, coefficient of discharge Cd and non-dimensional thickness t^*.

III. Numerical Methodology

The flow in the atomizer is considered to be axisymmetric, incompressible, unsteady, multiphase flow. A laminar model is adopted as it has proven to be more accurate in predicting the air core inside the pressure swirl atomizer[18]. The entire flow field is solved for mass and momentum conservation equations assuming zero circumferential gradient in the flow whereas non-zero swirl velocities are accounted.

$$\frac{\partial V_z}{\partial z}+\frac{\partial V_r}{\partial r}+\frac{V_r}{r}=0 \quad (3.1)$$

$$\frac{\partial V_z}{\partial t}+V_z\frac{\partial V_z}{\partial z}+\frac{2V_r(r\partial V_z)}{r} = -\frac{\partial P}{\rho\partial z}+2\frac{\partial}{\partial z}\left(\nu_{eff}\frac{\partial V_z}{\partial z}\right)+\frac{\partial}{r\,\partial r}\left(r\nu_{eff}\left(\frac{\partial V_r}{\partial z}+\frac{\partial V_z}{\partial r}\right)\right) \quad (3.2)$$

$$\frac{\partial V_r}{\partial t}+V_z\frac{\partial V_z}{\partial z}+\frac{V_\theta^2}{r}+\frac{V_r\partial(rV_r)}{r\,\partial r}=-\frac{\partial P}{\rho\partial r}+\frac{1}{r}\nu_{eff}\left(\frac{\partial}{\partial r}\left(r\frac{\partial V_r}{\partial r}\right)-\frac{V_r}{r}\right)+\frac{\partial}{\partial z}\left(\nu_{eff}\left(\frac{\partial V_r}{\partial z}+\frac{\partial V_z}{\partial r}\right)\right) \quad (3.3)$$

$$\frac{\partial V_\theta}{\partial t}+V_z\frac{\partial V_\theta}{\partial z}+V_r\frac{\partial(rV_\theta)}{r\partial r}+\frac{V_r\partial V_\theta}{r}=\frac{1}{r}\left\{\nu_{eff}\left(\frac{\partial(rV_\theta)}{\partial r}-\frac{V_\theta}{r}\right)\right\} \quad (3.4)$$

Equation (3.1) is mass conservation for unsteady, incompressible flow. Eqs. (3.2) to (3.4) are for conservation of momentum in axial, radial and tangential direction respectively. The air core inside the atomizer is captured by VOF multiphase model. A scalar phase volume fraction is defined such that it varies from one (primary phase) to zero (secondary phase) in each Eularian computational cell. The value in between 0 to 1 depicts an interface. This scalar is used to average out the density and viscosity values in Eqs. (3.2) to (3.4). The mean values of viscosity and density are calculated by Eq. (3.5) and (3.6) respectively.

$$\rho=\rho_1\alpha+\rho_2(1\text{-}c) \quad (3.5)$$

$$\mu=\mu_1\alpha+\mu_2(1\text{-}c) \quad (3.6)$$

$$\frac{\partial\alpha}{\partial t}+u\cdot\nabla\alpha=0 \quad (3.7)$$

The Volume fraction is accounted by Eq. (3.7) and is solved simultaneously with Eqs. (3.1) to (3.4) .The time discretization is done with an implicit scheme, interpolation near the interface is done by geo-reconstruct scheme. The pressure-velocity coupling in momentum equations is accomplished by Pressure Implicit with Splitting of Operator (PISO) scheme. Pressure Staggering Option (PRESTO) is selected for spatial discretization as the atomizer has high swirling flow. ANSYS FLUENT 16 is used to solve the governing equations.

The fluid enters the atomizer from finite number of inlet ports tangentially placed at the base of swirl chamber which makes the inlet three dimensional. Therefore, axisymmetric assumption is made by defining an equivalent annular inlet slot such that tangential and radial velocities at 2D inlet have same volumetric flow rate and circumferential velocity as the 3D inlet.The unsteady simulations were conducted till the mean deviations in inlet pressure, mass flow rate and spray angle with respect to time were negligible. The air core diameter is calculated by considering volume fraction of 0.5 iso-surface for water phase. The validation of numerical model is done by comparing it with experimental results of Dash et.al[18]. A grid-independence test was done on coarse grid of 10,404 elements and refined grids of 85685 elements. Gradient adaption based on volume fraction of water was done on both the grids.

Table 3.1. Grid independency test for computational domain

Parameters	**Coarse grid results**	**Refined grid results**	**Experimental Results**
Size	10404	85685	NA
d_a (middle of orifice)	1.23 (mm)	1.24(mm)	1.15(mm)
ψ	32.25°	31.56°	27°-29°

IV. Results and Discussion

The analysis was carried out on three types of atomizers as stated in Table 4.1. The atomizers having straight section and divergent section in orifice are denoted by S and D respectively whereas C notation is used for atomizer configuration having combination of straight and divergent section in the orifice as shown in Fig 1.1. These atomizers were numerically investigated to determine the effect on spray angle, non-dimensional thickness and coefficient of discharge. The parameter, non-dimensional thickness t_f is a ratio of liquid film thickness at orifice exit to the orifice radius. This parameter was used to normalize the effect of changes in outlet orifice diameters of various atomizer configurations.

Table 4.1. Atomizer configurations

Atomiser	D_o (mm)	D_t (mm)	L_o (mm)	Lt (mm)	D_s(mm)
D1	-	2.7	-	4	8
S1	2.7	-	4	-	8
S2	2	-	4	-	8
C1	2	3.4	4	4	8
C2	2	3.4	2	6	8
C3	2	3.4	6	2	8

4.1Effect of replacing straight section with divergent section in orifice, having same orifice diameter.

Majority of the pressure swirl atomizers used in practice have a straight section in the orifice .The straight section is replaced with a diverging section and its effect on internal parameters is investigated. The comparison is made with S1 atomizer having a straight orifice section with same L_o/D_o ratio.The angle of divergence is 5° and mass flow rate of $5.3x10^{-3}$ m^3/s is same for all configurations. From Table 4.2, it is observed that the non-dimensional thickness and spray angle decreases by 45% and 38% respectively for D1 when compared with S1 having a straight section with same orifice exit diameter. The reason for decrease in spray angle is attributed to a lower axial velocity for S1 atomizer at orifice exit as seen in Fig.4.1 (a). D1 configuration has greater axial velocity even though it has a diverging section. This due to a smaller orifice entry diameter for S1 configuration compared to D1.The difference in orifice diameter at entry, is a result of maintaining a constant L_o/D_o relation for both the configurations.Therefore a further comparison of D1 configuration with an atomizer S2 having same orifice entry diameter with only a straight section is done.

Table 4.2. Internal flow parameters for D, S1 and S2 configurations

Atomizer	t_f	ψ	Cd
D1	0.144	48.36	0.23
S1	0.263	77.78°	0.33
S2	0.247	64.5	0.41

From Table 4. 2, atomizer D1 still has 42% lower non-dimensional thickness and 25% lower spray angle when compared to S2. In Fig.4.1 (a), the negative velocities indicate the reverse flow of air entering the atomizer which eventually leads to the formation of air core. The positive velocity magnitudes are for liquid sheet and the air which leave the atomizer while recirculating. It is observed that D1 has the lowest axial velocity in the air core region, therefore by conservation of mass it leads to the formation of bigger air core compared to S1 and S2. The bigger air core thus squeezes the liquid sheet exiting the atomizer which results in D1 having the lowest non-dimensional thickness of all the atomizers compared.

The value of Cd, depends upon the pressure drop across the atomizer. It is calculated numerically by Eq. (4.1).The value of m_a is constant for all atomizer configuration. A_o is the orifice exit diameter, ρ_l is density of water and is calculated numerically .It is observed that S2 has the highest value of Cd nearly twice that of atomizer D1. This is due to a higher liquid film thickness generated in S2 atomizer which discharges more amount of liquid compared to other atomizers.

$$Cd = \frac{m_a}{\rho_l A_o \sqrt{\frac{2\Delta P}{\rho_l}}} \quad (4.1)$$

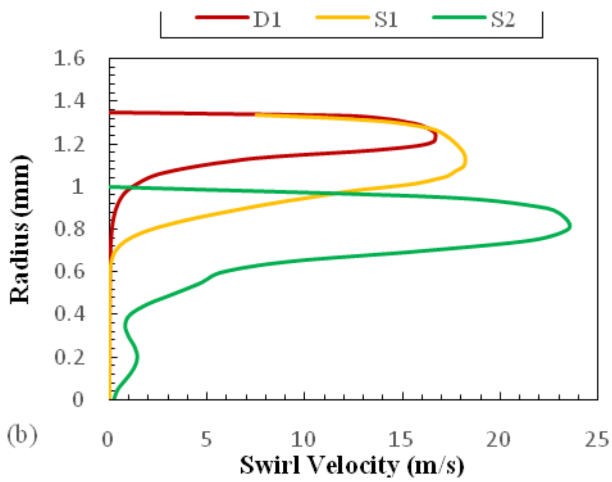
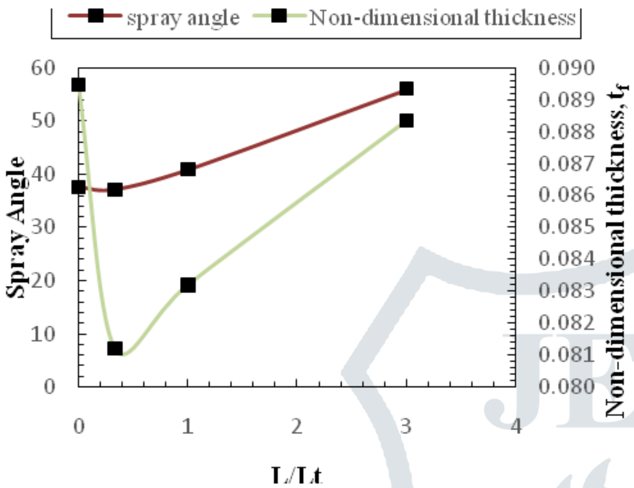


Fig. 4.1. Velocity profiles at orifice exit for D1, S1 and S2 configurations: (a) Axial velocity; (b) Swirl Velocity

4.2Effect of replacing straight and divergent section with single divergent section in orifice, having same inlet and outlet orifice diameter.

The atomizer performance in terms of spray angle and non-dimensional thickness is analyzed for D and C types of atomizers. The results are presented in Fig.4.2. The value of 0 for L/Lt indicates that the orifice has only divergent section; therefore D1 is used. C1, C2 and C3 have values of 0.3,1 and 3 respectively.

It is observed that the spray angle is constant and minimum till L/Lt= 0.3, thereafter it keeps on increasing. The non-dimensional thickness indicates the liquid film thickness at the exit of the orifice. Its value is seen to be maximum for D1 atomizer corresponding to zero L/Lt value. The value drops at L/Lt value of 0.33 and thereafter increases monotonically till L/Lt value of 3. Furthermore it is observed that, the value of 0.33 for L/Lt gives a minimum spray angle and non-dimensional thickness.



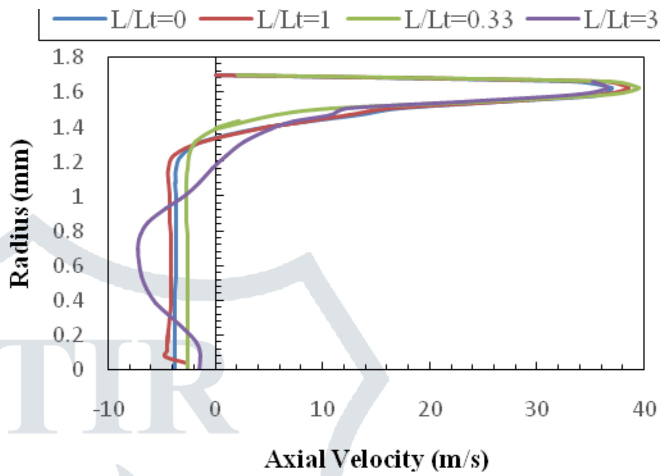


Fig. 4.2. Spray angle and non-dimensional thickness for various atomizer configurations

Fig. 4.3. Axial velocity profile for various configurations at orifice exit

It is observed from Fig. 4.3, atomizer C2 having L/Lt=0.33 has the highest axial velocity at the orifice exit when compared to the other atomizers. Consequently, it has the lowest spray angle. C2 has lower velocity in air core region which reduces the liquid sheet thickness at the orifice exit. The angle of divergent section increases as the value of L/Lt increases for same inlet and outlet orifice diameter as seen in Table 4.3. Therefore, as angle of divergent section increases the spray angle increases after L/Lt = 0.33. Table 4.3 shows the coefficient of discharge for various atomizer configurations. It is observed that the values of Cd are near about constant for C type of atomizers (having both straight and diverging section in orifice). D1 type of atomizer is able to provide a greater Cd value as it encounters a lower pressure drop compared to C type of atomizers.

Table 4.3. Coefficient of discharge for various atomizer configurations.

L/Lt	Atomizer	Cd	Divergent Angle
0	D1	0.148401	5
0.33	C1	0.138718	6.7
1	C2	0.140792	10
3	C3	0.140281	19.4

V. CONCLUSION

A CFD based approach using ANSYS FLUENT 16 was used to predict the two-phase flow inside a simplex atomizer.The effect of replacing straight section with divergent section and the dependence of internal flow parameters on the non-dimensional parameter L/Lt is not fully investigated in the literature. Therefore the results presented in this paper will be helpful for designing atomizers with divergent sections where low spray angles are warranted. The internal flow parameters investigated in this study were spray angle, non-dimensional thickness and coefficient of discharge. The conclusions are as follows

- When straight section is replaced by divergent section, it produces a lower spray angle compared to an atomizer having either the same inlet orifice diameter or the same outlet orifice diameter.
- The liquid sheet thickness and coefficient of discharge is found to be lower in an atomizer having only divergent section than with an equivalent straight section atomizer
- For an atomizer having same inlet and outlet orifice diameter, the value of 0.33 for L/Lt produces minimum spray angle and non-dimensional thickness.
- The spray angle and non-dimensional thickness are seen to increase with L/Lt after it reaches a minimum at 0.33
- The coefficient of discharge is highest for an atomizer having only divergent section compared to atomizers having a combination of straight and divergent section.

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