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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF A PRESSURE SWIRL ATOMIZER FLOW FIELD

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ABSTRACT

Pressure swirl atomizers have a wide variety of application area in the industry from the combustion systems to industrial applications. In this study, characteristics of a pressure swirl type atomizer, which is designed and manufactured in TÜBİTAK SAGE, are investigated numerically and experimentally. Empirical correlations are used to estimate the basic parameters of the atomizer and these parameters are used to manufacture the atomizer. A commercially available flow solver FLUENT is used to perform the numerical simulations. Volume of Fluid (VOF) model is chosen to be the modeling method for the atomizer flow field investigation. For the experiments a 2-D Phase Doppler Particle Analyzer (PDPA) system is used to measure the droplet size classes and velocities of the droplets. Velocity vector field of gaseous phase is also obtained from the experiments. In addition to PDPA measurements, a high speed shadowgrapy system is also used for visualizing the flow field. Although, droplet size classes cannot be obtained from the numerical simulations, velocity field obtained from experiments compared with the numerical results.

INTRODUCTION

Pressure swirl atomizers are one of the simplest types of atomizers. Pressurized liquid flows through the tangential ports to the swirl chamber of the atomizer. Due to swirling of the liquid, pressure at the center of the atomizer decreases such that surrounding air sucked into the atomizer and at the exit of the atomizer a liquid film appears. This liquid film has both axial and swirl velocities. When the liquid film leave the nozzle, a hallow cone liquid film formed at the exit of the atomizer. Shear forces due to surrounding media disturbs the liquid film and liquid film starts to disintegrate and ligaments forms. Further downstream, ligaments disintegrate into droplets and a hollow cone spray formed [Lefebvre A.H, 1989].

Although Pressure Swirl Atomizers are being used rather frequently in industrial applications, rocket engines and air-breathing propulsion over last century, with the increasing computational and experimental abilities, research effort continuously growing on these type of atomizers. [Khavkin Y.I., 2004; Nonnenmacher S. and Piesche M., 2000].

Recently numerical simulations performed by [Datta A. and Som S.K., 2000: Hinckel J.N. et al., 2008] and [Sumer B. et al., 2012] on pressure swirl atomizer to obtain air core diameter, film thickness, spray cone angle and pressure drop. In terms of internal flow field simulations of the pressure swirl atomizers, the usage of Volume of Fluid model is proved in the literature.

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Also in the last decade with the developing experimental techniques like Phase Doppler Particle Analyzer (PDPA) technology, experimental measurements performed on pressure swirl atomizers. [Bachalo W.D. and Houser M.J., 1984; Santayola J.L. et al., 2010]. Santayola et al. investigated the velocity vector fields for different droplet size classes and volume flux distribution through the flow field.

In this study, a pressure swirl atomizer is designed by using empirical equations and manufactured. Numerical investigation of the atomizer internal and external flow field is performed with a commercial flow solver. Moreover, by applying a high speed shadowgraphy technique cone angle and break-up distance measured. In order to obtain the droplet size classes and velocity field, a 2-D PDPA system used in the experiments.

Atomizer Design Study

In order to design a pressure swirl atomizer some of the parameters have to be set prior to start design procedure. The basic parameters are Sauter Mean Diameter (SMD), Cone angle, flow rate and manufacturing limits. For this study SMD is chosen to be 60 μm, which is rather acceptable value for combustion applications. [Lefebvre A.H., 1999]. Cone angle is selected to be 120°, which is quite a high value for pressure swirl atomizers; however in combustion system, increasing the cone angle widens the flame and increases stability.

The Sauter mean diameter (SMD) of the resulting spray can be estimated using the empirical equation of [Wang and Lefebvre, 1987]

$$SMD = 4.52\left(\frac{\sigma\mu_l^2}{\rho_a \Delta P_l^2}\right)^{0.25}(t\cos\theta)^{0.25} + 0.39\left(\frac{\sigma\rho_l}{\rho_a \Delta P_l}\right)^{0.25}(t\cos\theta)^{0.75} \tag{1}$$

In order to calculate the SMD value of the atomizers, spray cone angle has to be calculated. Equation (2), which is proposed by [Rızk and Lefebvre, 1985] can be used to estimate this parameter.

$$2\theta = 6\left[\frac{D_s d_o}{A_p}\right]^{0.15}\left[\frac{\Delta P_l d_0^2 \rho_l}{\mu_l^2}\right]^{0.11} \tag{2}$$

Another important parameter to calculate the SMD is the film thickness “t”. [Giffen and Muraszew, 1953] proposed the following equation for the calculation of film thickness.

$$\frac{(1-X)^3}{(1+X)} = 0.09\left(\frac{A_p}{D_s d_0}\right)\left(\frac{D_s}{d_0}\right)^{0.5} \tag{3}$$

Where X can be calculated as,

$$X = \frac{(d_0 - 2t)^2}{d_0^2} \tag{4}$$

By solving the equation (3) one can obtain the film thickness of the atomizer. It is interesting that the film thickness is only a function of geometric parameters of the atomizer.

After iterating over the above parameters while taking into account the manufacturing issues, an atomizer is chosen for investigations. The geometric and flow properties calculated with above empirical relations are given in Table 1. The 3-D CAD model of the atomizer is given in Figure 1.

Table 1: *Atomizer Parameters*

Geometric Properties	Orifice Diameter (d_o)	3.2 mm
	Port Diameter (d_p)	0.8 mm
	Number of Ports (n)	2
	Swirl Chamber Length (L_s)	10.6 mm
	Swirl Chamber Diameter (D_s)	10.6 mm
Flow Properties	Cone Angle (θ)	117.5°
	Film Thickness (t)	0.161 mm
	Mass Flow Rate	20.9 g/s
	ΔP_l	2.55 bar
	SMD (Sauter Mean Diameter)	57.61 µm
Fluid Properties	Density of Water	1000 kg/m^3
	Viscosity of Water	0.001 kg/s^2
	Density of Air	1.050 kg/m^3

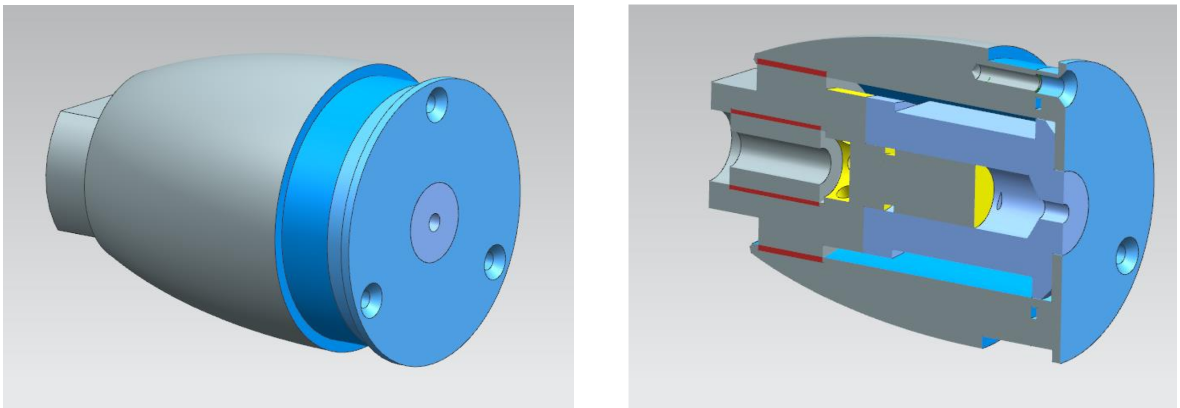


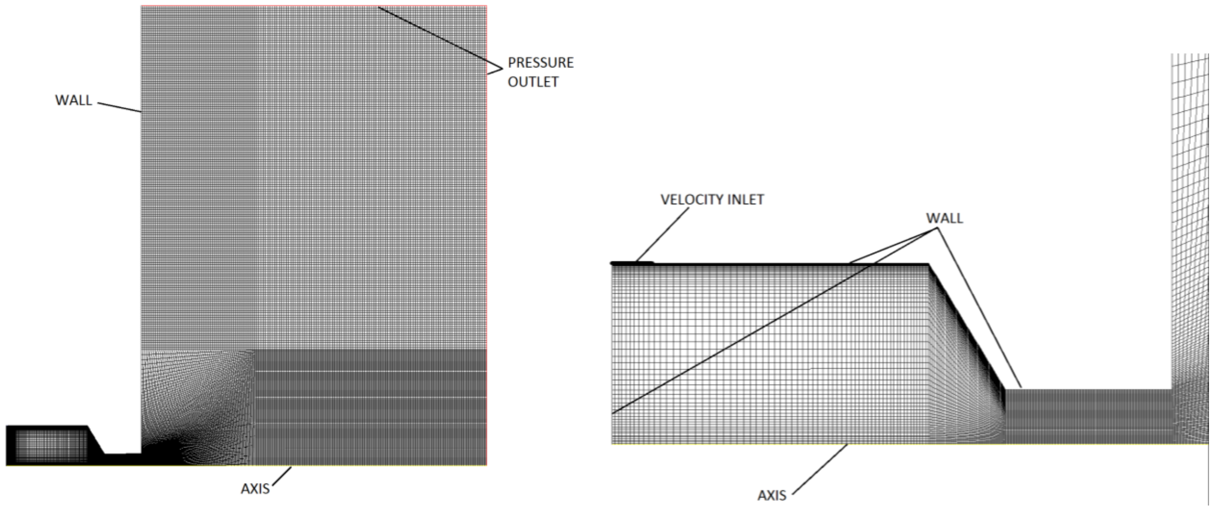
Figure 1: 3-D CAD model of the atomizer assembly

METHOD

The ability of predicting the different flow parameters with empirical relations, numerical simulations and experiments is fairly different. With the use of empirical relations basic parameters like Cone angle, SMD, film thickness and nozzle exit velocities can be estimated with less accuracy. However, one must be very careful while using these equations due to the fact that they are only valid for a limited range of parameters. Therefore, more complicated numerical simulations have to be performed in order to estimate the parameters with higher accuracy. In this study, Volume of Fluid (VOF) [Hirt C.W. and Nicholas B.D., 1981] approach is used to solve the velocity field inside the swirl chamber and downstream of the atomizer. However, the limiting condition for this method is that the film disintegration cannot be modeled and the results of the numerical simulation tend to be away from the real physics of the atomizer flow at downstream of the break-up location. The only way of obtaining the droplet size classes and break-up length of the atomizer is the experiments. Therefore, a high speed camera is used to measure the break-up length and cone angle and a 2-D Phase Doppler Particle Analyzer is used to measure the droplet sizes and velocities. However, the internal parameters like film thickness and nozzle exit velocities cannot be measured in this study.

Numerical Method

Physical phenomenon inside and outside the pressure swirl atomizers are rather complicated to be estimated by simple correlations. Although some empirical models developed for the estimation of basic characteristic parameters of the flow, computational fluid dynamics has to be applied in order to understand and model this complex flow field. The interaction between the liquid phase and gaseous phase has an important effect on flow field. A commercially available flow solver ANSYS-FLUENT is used in the CFD calculation. To model the multiphase interactions, Volume of Fluid (VOF) model is chosen. In this study, flow field is assumed to be 2-D axisymmetric due to computational power limitations. Also in the literature, there exist axisymmetric CFD simulations for pressure swirl atomizers, which give a good agreement with the experimental results. In Figure 2, mesh and boundary conditions are given, which are used for the numerical simulations.



a) b)

Figure 2: *Solution Domain & Boundary Conditions*

“Pressure outlet” boundary condition is applied for the right hand side and for the upper boundary of the simulation domain. At the bottom “axis” boundary condition has to be applied for the axisymmetric simulations. Because, the modeling of tangential ports of the atomizer is impossible for axisymmetric simulation, a “velocity inlet” boundary condition is applied to the upper left corner of the pressure swirl atomizer with applying swirl and radial velocity components at the same time. [Dash S.K. et al., 2001] For the calculations, 58000 cell, hexagonal grid is used.

An implicit axisymmetric Pressure Based solver which solves the swirl component addition to x and y components is used with 1st order implicit time discretization. For the multiphase physics, explicit Volume of Fluid model is applied. Both phases assumed to be incompressible. Assuming, the effect of heat transfer is quite small, energy term in Navier-stokes equation is omitted. Moreover, the flow inside the atomizer is assumed to be laminar. For the discretization, PRESTO scheme is used for pressure and Modified HRIC [Muzafferija S. et al., 1998] is used for the volume fraction calculations. To increase the stability, time step is chosen to be 2.0e-6s. The denser fluid water is chosen to be Phase-1 and air is chosen to be Phase-2 in order to increase the stability of the numerical simulations, as it is recommended in the software user manual.

Experimental Method

<u>Experimental Setup</u>

A sketch of experimental setup is given in Figure 3. Pressure Swirl Atomizer assembly is fed by and high pressure water tank, which can be pressurized up to 200 bars and pressurized by an industrial type pressure regulator and nitrogen gas bottle. A shut-off valve is used for initiation of the flow and with the help of a flow meter flow rate is measured. A needle valve is also attached to the line in order to control the mass flow rate. Upcoming spray from the atomizer is then visualized by high speed cameras and droplet measurements performed with Phase Doppler Particle Analyzer system.

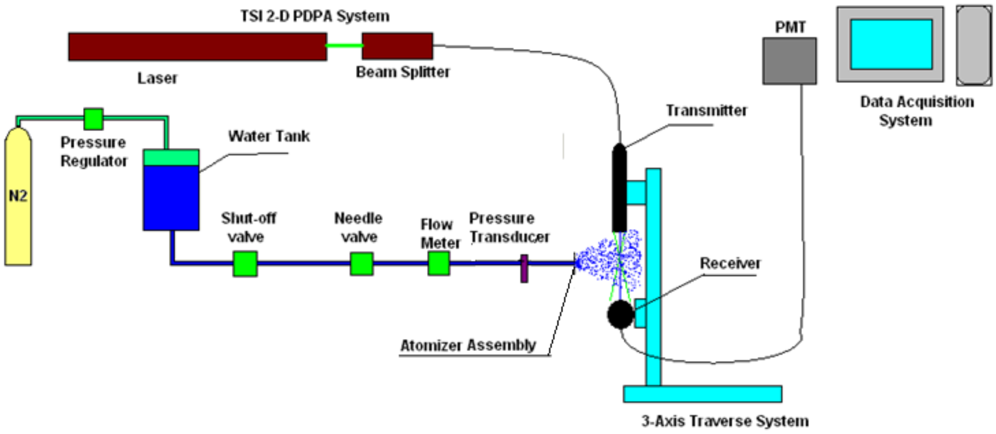


Figure 3: *Experimental Setup*

High Speed Shadowgraphy

In order to obtain cone angle and break-up length, a high speed shadowgrapy system is used prior to PDPA measurements. In Figure 4, Shadowgraphy setup is given. System composed of a high speed Photron SA 1.1 camera, Nikkor 105 mm lens and a halogen light source. A diffuser is placed in front of halogen light source in order to have a better visualization. The frame rate of the camera set to 90 kHz and at that rate the effective image area is 384x128 pixels. Acquired images are investigated with the image processing tool of MATLAB software.

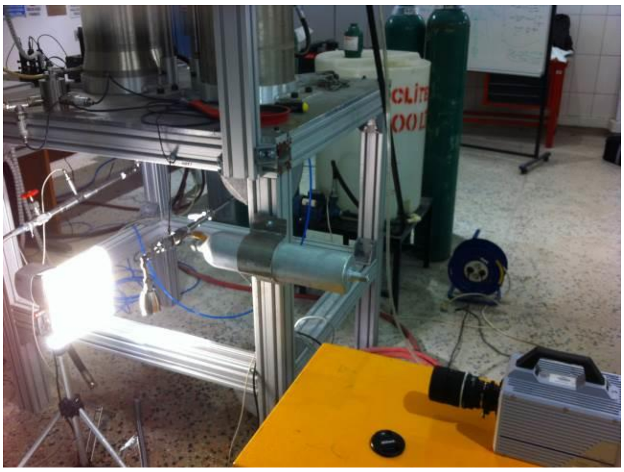


Figure 4 : *High Speed Shadograpy System*

Phase Doppler Particle Analyzer

In the second part of the experiment a 2-D PDPA system (TSI) is used to measure the droplet size classes and velocities. The Sauter Mean Diameter (SMD) values are calculated with FlowSizer software of TSI Company. Measurement performed on eight axial locations starting from 15 mm downstream of the atomizer exit. In each axial location, Travers mechanism used to move the probe in radial direction in order to measure radial distribution of the spray flow field. In Figure 5, orientation of PDPA transmitting optics and atomizer assembly can be seen. Power of Ar-Ion Laser is set to 300mW for the measurements and 250 mm beam splitter lens is used for high accuracy on the droplet size classes generated by the atomizer.

Figure 5: *2-D PDPA (TSI) Transmitting Optics*

Velocity vectors corresponding to two different droplet size classes are calculated with FlowSizer software. Smaller droplets, which have a diameter less than 10 μm, tends to follow the air flow field and the bigger droplets, which have a diameter greater than 50 μm, maintains their momentum through their trajectory on the flow field. [Bachalo W.D. et al., 1993; Albrecht H.E., 2003] Therefore, the velocity vector field of smaller droplets shows the gaseous phase velocity field and the velocity vector field of bigger droplets shows the atomizer nozzle exit velocity conditions.

RESULTS & DISCUSSION

In this section, the results obtained from the numerical simulations and experimental work is discussed. In the first part, the results of numerical simulations are given. In the second part the results of the high speed shadowgraphy and PDPA measurement are given. In the last part the numerical and experiment results compared with each other.

Numerical Simulations

The numerical simulations performed for a time period of 410 ms. At the initiation phase, swirl chamber is full of surrounding air and liquid phase start to enter from the velocity inlet boundary. After 27 ms, swirl chamber filled up with liquid phase and liquid film appears at the exit of the atomizer. The results presented in Figure 6, Figure 7, Figure 8 and Figure 9 are time averaged values starting from 27 ms.

In Figure 6, mean volume fraction of liquid phase is plotted. For the liquid phase the value “1” represents liquid phase and “0” represents gaseous phase. As one can interpret from the figure that the gaseous phase entrained in to the swirl chamber due to suction created by the swirling velocity field inside the atomizer. Then at the exit of the nozzle liquid phase makes a sharp angle with the axial-axis and creates a hallow cone liquid film. Liquid film cone getting thinner moving through downstream and diffuses at a certain location. The disintegration of liquid film and ligament forming cannot be captured with this model.

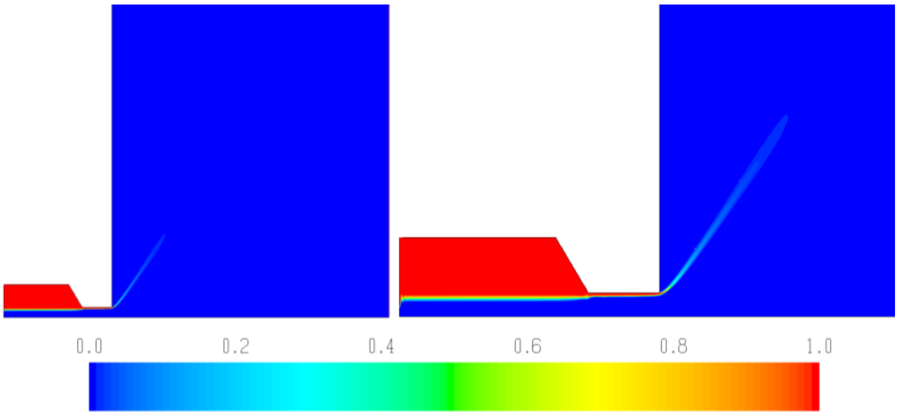


Figure 6: *Mean Volume Fraction of Phase-1 (Liquid) Contour Plot*

In Figure 7, Figure 8 and Figure 9 mean axial velocity, mean radial velocity and mean swirl velocity fields plotted respectively. As it can be seen from first figure a strong recirculation created by the liquid film emerging from the atomizer exit. At the further downstream axial velocity diffuses and the effect of film decreases. In Figure 8, radial velocity appears just at the downstream of the atomizer exit and again diffuses after a certain distance. Also the swirl velocity of the liquid film at the exit of the atomizer decreases suddenly after liquid phase leave the nozzle.

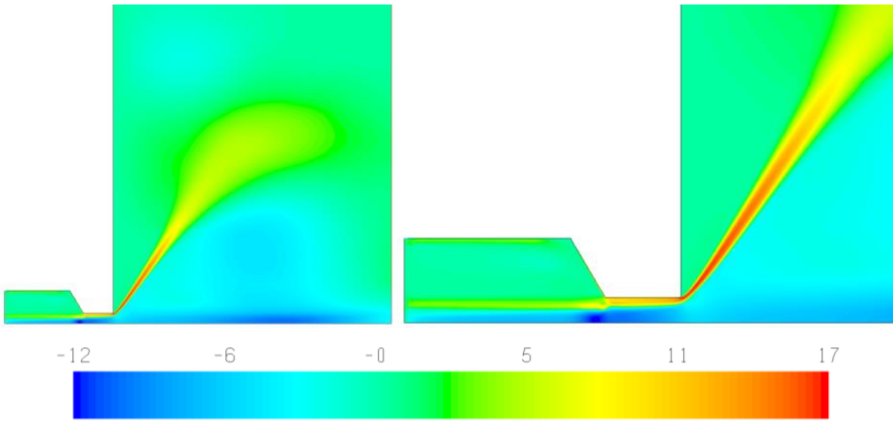


Figure 7: *Mean Axial Velocity Field (m/s)*

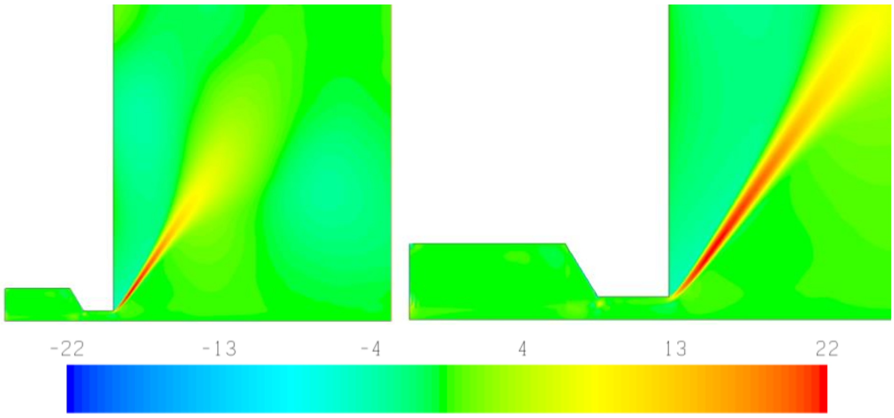


Figure 8: *Mean Radial Velocity Field (m/s)*

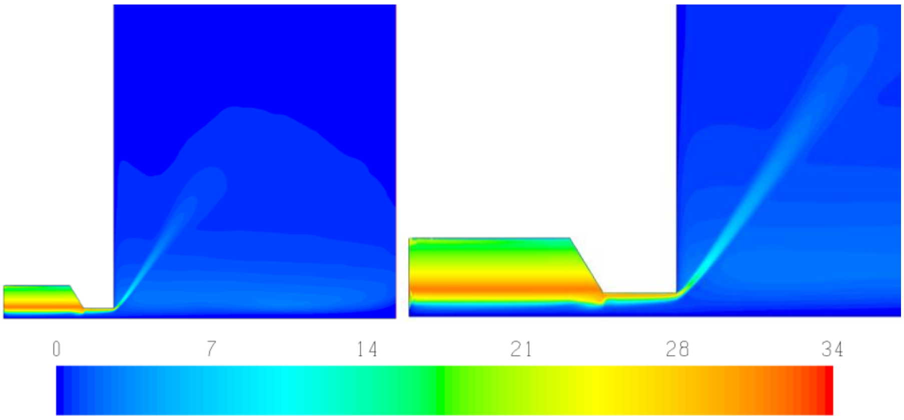


Figure 9: *Mean Swirl Velocity Field (m/s)*

Experiments

High Speed Shadowgraphy

The snapshot obtained from the high speed camera is given in Figure 10. With the use of a reference length and MATLAB image processing tool box, cone angle and break-up length is obtained for the atomizer. However, it is not easy to distinguish the break-up point exactly. Therefore, a rough estimation made for that parameter. The break-up length is chosen to be the point where the ligaments disappear and drops appear.

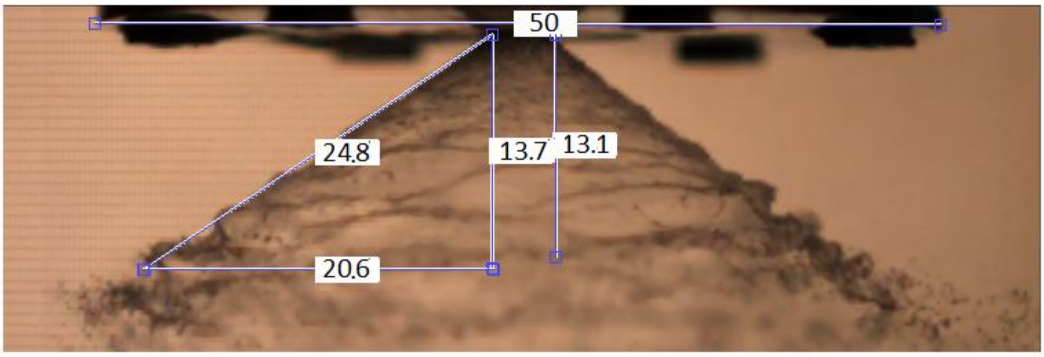


Figure 10: *Image Processing of Spray (Dimension in mm)*

For the designed Pressure Swirl Atomizer cone angle is measured as 112.63° and the break-up length is measured as ~13.1 mm.

Phase Doppler Particle Analyzer Measurements

Starting from 15 mm downstream of atomizer nozzle PDPA measurement performed at eight axial locations with 5 mm steps. At each location, moving through radial axis and starting from center line of the atomizer to the edge of the spray with 5 mm steps, data collected. In Figure 11 Sauter Mean Diameter values calculated by FlowSizer software is plotted.

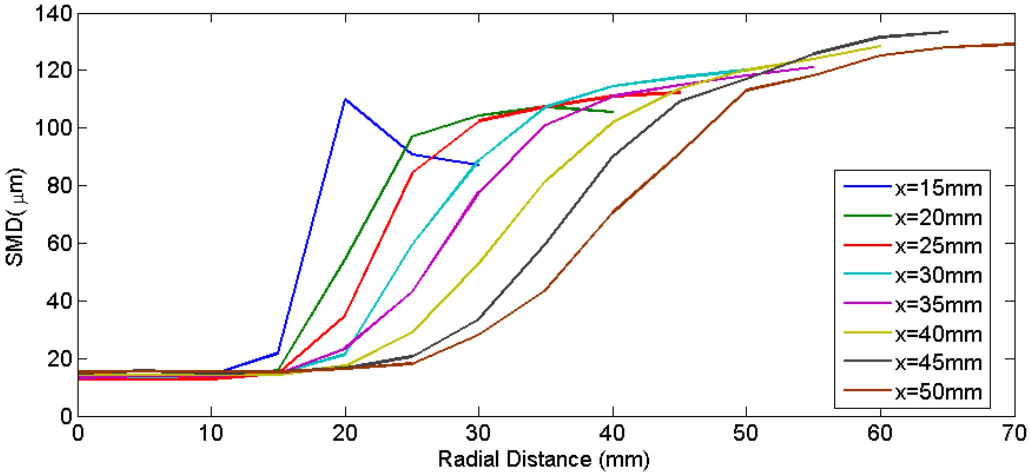
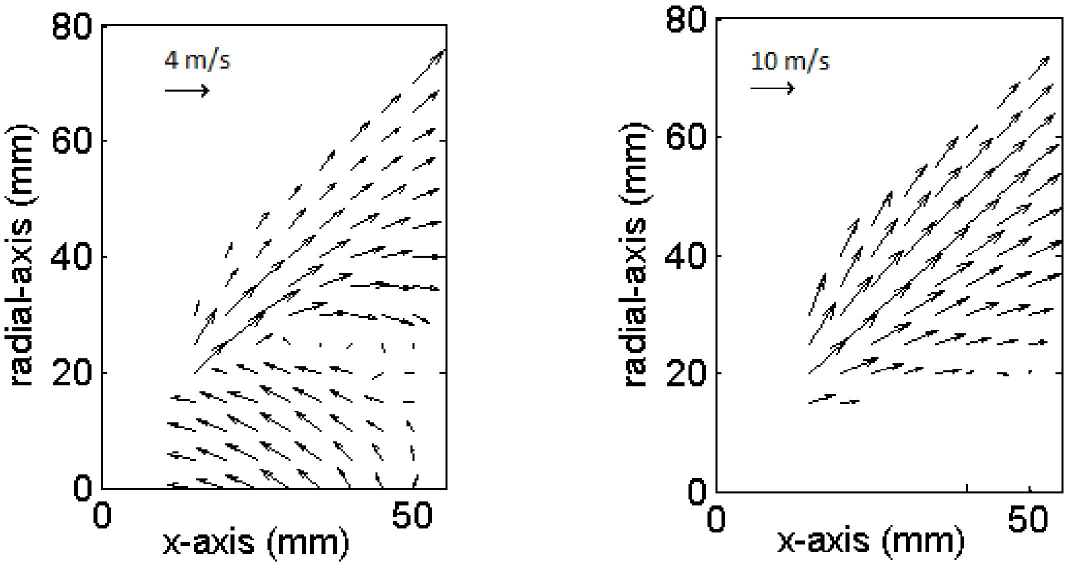


Figure 11: *Sauter Mean Diameter Distribution*

At x=15 mm line SMD value creates a peak which can be attributed to break-up effect. This location is just 2mm away from the estimated break-up distance therefore the measurements can be effected by this phenomenon. Progressing through downstream locations, peak SMD values slightly increases and a wider distribution appears as expected. The maximum SMD value obtained with PDPA is higher than the empirically predicted 57 μm. Also as it is expected, smaller droplets placed at the centerline and the bigger ones tend to move with their initial velocity while maintaining their momentum. [Santayola et al., 2010]

In Figure 12 velocity vectors plotted for two different droplet size classes. Droplets having smaller diameter tends to follow the gaseous phase velocity field and the bigger ones maintains their momentum and velocity through the flow field. Therefore, the smaller droplets follow the recirculating flow at the centerline thus, the velocity of these droplets smaller than the bigger ones. Due to momentum transfer between the dispersed phase and gaseous phase, although experiments performed in quiescent air, surrounding air accelerated to a certain velocity.



a) Droplet Diameter < 10μm b) Droplet Diameter > 50μm

Figure 12: *Vector Field*

In Figure 13, the value of "q" calculated by FlowSizer software is given for two axial locations. This parameter shows the droplet size distribution at the measurement point (Equation (5)). When "q" small, the Gaussian distribution of the droplet sizes squeezed, for the higher "q" values diameter distribution flattens. [Lefevbre A.H., 1989] For this atomizer, moving 5 mm downstream increases the spread of droplet size distribution.

$$1 - Q = e^{\left(\frac{\ln D}{\ln X}\right)^q} \quad (5)$$

Where, Q is the fraction of the total volume contained in drops of diameter less than D. $X = D_{63.2}$ and q are constants.

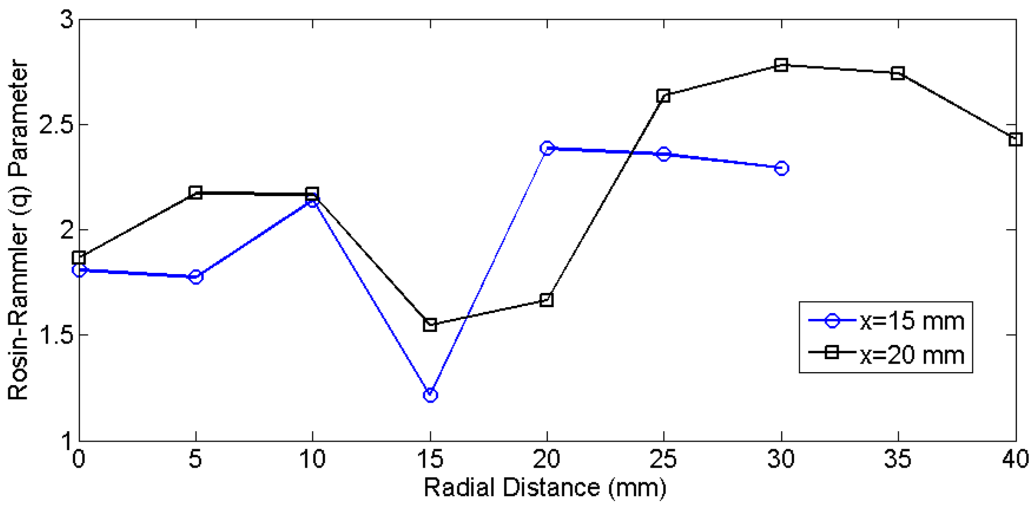


Figure 13: *Rosin-Rammler q parameter distribution*

Comparison of the Numerical Simulations & Experimental Measurements

The results of the empirical relations, numerical simulation and experimental measurements are given in Table 2. As it can be seen, cone angle values obtained from the numerical simulations and experiments are quite close. Due to the fact that empirical relations does not account for the friction effect and boundary layers, pressure drop values are away from measurements and numerical simulations. This loses decreases the axial velocity of the film at the nozzle exit and thickens the film at that location. As a consequence SMD values increases with the increasing film thickness.

Table 2: *Comparison of the Results*

	Empirical Relations	Numerical Analysis	Experimental Analysis
Cone Angle (θ)	117.5◦	110.1◦	112.6◦
Film Thickness (t)	0.161 mm	0.233 mm	-
Mass Flow Rate	20.9 g/s	20.9 g/s	20.8 g/s
SMD	57.61 μm	-	~100-120 μm
ΔP	2.55 bar	9.37 bar	8.3 bar
U_{nozzle} (axial)	13.58 m/s	12.58 m/s	*11.5 m/s
U_{nozzle} (radial)	-	-	*12.7 m/s
U_{nozzle} (swirl)	22.38 m/s	22.6 m/s	-

*Measured Velocity at location x=15 mm (>200μm droplets)

To compare the velocity distribution obtained from the numerical simulations and experiments, Figure 14 and Figure 15 plotted. For the comparison the velocities of the droplets less than 10 μm is used. Comparison made only for points closer to the break-up distance. At the downstream of x=20 mm line, the influence of droplets are increasing, which VOF method cannot take into account for the calculations. Calculated axial velocity distributions and measured ones have a good agreement except the difference at the center. Also radial velocity distribution fits quite well with the experimental results.

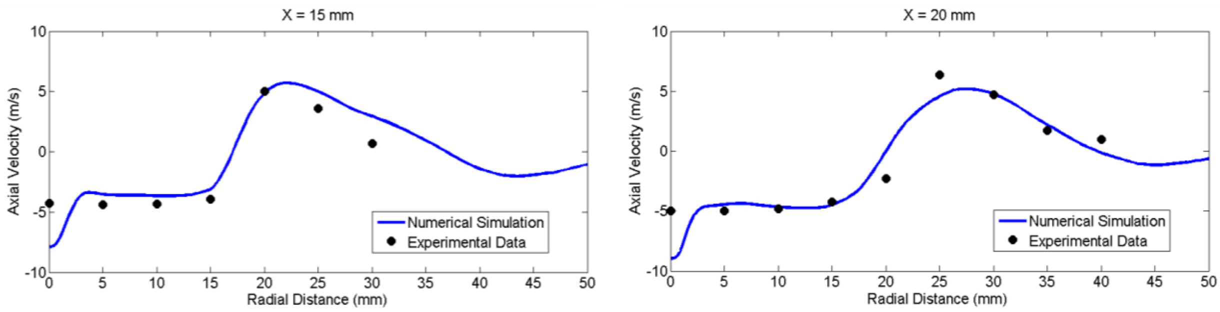


Figure 14: *Axial Velocity Comparison*

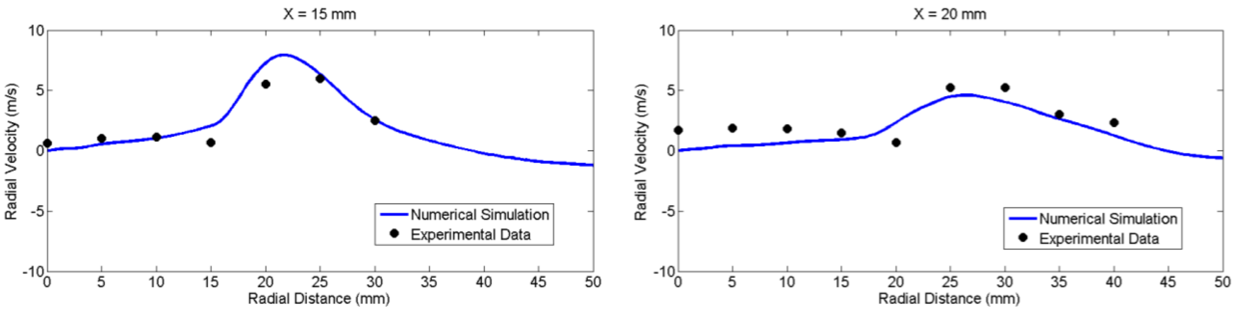


Figure 15: *Radial Velocity Comparison*

CONCLUSION

In this study, a pressure swirl atomizer is designed by using empirical correlations, numerically investigated with Volume of Fluid method, manufactured and subjected to experimental investigation. For the numerical simulations a commercial flow solver ANSYS-FLUENT is used. Although VOF method can estimate the cone angle, jet velocities and velocity field near the break-up point with a good accuracy, due to the limitations on disintegration of the liquid film in this model, after the break-up point model fails to predict the velocity distribution. Therefore, discrete phase models have to be integrated to the simulation in order to add the effect of momentum transfer between discrete phase and gaseous phase. Experimental results show that the measured SMD values are higher than the values obtained from empirical correlations. This can be originated from the fact that the SMD estimation equation developed by using a volumetric measurement device (Malvern). In that method, SMD values measured through a 2-D plane not from a point. Therefore, the droplet diameter values averaged through the measurement plane. The vector field obtained from PDPA measurements for small droplets shows positive radial velocity magnitude at the centerline, which may be attributed to existence of a bigger scale vortex at the core section of the atomizer. Further test has to be performed to investigate this phenomenon.

Acknowledgements

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Nomenclature

θ : Spray Half Cone Angle (deg)

μ_l : Dynamic Viscosity of Working Fluid (kg/s^2)

ρ_a : Density of Surrounding Media (kg/m^3)

ΔP_l : Pressure Drop Across Atomizer (Pa)

t : Film Thickness (m)

ρ_l : Density of Working Fluid (kg/m^3)

D_s : Diameter of Swirl Chamber (m)

d_0 : Orifice Diameter (m)

A_p : Port Area (m^2)

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