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Numerical Analysis and Empirical Correlations to Predict SMD of Pressure Swirl Atomizer for Small Scale Gas Turbine Combustion Chamber

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Abstract

The use of Small Gas Turbine to meet on-site small-scale energy demand offers a great opportunity for preliminary energy saving and reduction of pollutant and greenhouse emissions. The properly designed atomizer can reduce emission and impart flame stability. The Sauter mean diameter of atomizer plays an important role in the combustion chamber performance. There are number of empirical and semi empirical equations are developed to find Sauter mean diameter of the spray from pressure swirl atomizer. In the present work numerical simulation of pressure swirl atomizer for small scale gas turbine combustion chamber is carried out using ANSYS Fluent and SSD model is selected as secondary droplet breakup model. The effect of injection pressure on the Sauter mean diameter is studied and the results are compared with empirical correlations available in literature.

Keywords: pressure swirl atomizer, SSD, SMD, numerical simulation, empirical correlation.

INTRODUCTION

Because of simple geometric construction and good atomization characteristics, the pressure swirl atomizer are generally used for gas turbine engine and industrial furnaces [1]. The combustion process, flame stability and combustion efficiency depends on performance of atomizer. The Sauter mean diameter (SMD) is one of the important spray characteristics and widely acceptable to explain atomizer performance

The transformation of bulk of liquid into spray of small droplets from pressure swirl atomizer is simple principle but various internal flow through pressure swirl atomizer make the atomization process very complex. The SMD depends on atomizer geometry, property of liquid and operating conditions. The SMD generally derived from empirical equations but there are very less published empirical equations that relate SMD with all dependant parameters (geometry, liquid property and operating conditions). That increase the need of selection of correct available equations for combustion applications.

CFD analysis becomes very useful tool to solve complex phenomena of atomization process. There are number of models developed to solve atomization process. The theoretical and experimental studies on pressure swirl atomizer and flow phenomena had been reviewed in detail by Lefebvre [1]. Brickman et.al. [2] studied the different physical phenomena of atomization process. Recent CFD models for atomizers are highly sensitive to spray origin parameters [3].

In the present work the pressure swirl atomizer, designed earlier for small scale gas turbine combustion chamber, is analysed using CFD tool – ANSYS Fluent [3]. The Sauter Mean Diameter (SMD) is analysed using Stochastic Secondary Droplet (SSD) model and the results of numerical analysis are compared with empirical equations.

NUMERICAL SIMULATION

The fluid flow through atomizer and after injection of fluid are totally different. The experimental analysis of atomization characteristics are time consuming and expensive while Computational fluid dynamics (CFD) analysis is the present state- of – art technique for fluid flow analysis. The continuous and dispersed (particle) flow can easily modelled and analysed with CFD. For atomization process, there is an interaction between two phase, gas/liquid, occurs. In the present case the gas is considered as continuous phase and Navier – Stokes equations are solved and liquid is as discrete phase and solved by tracking droplets in flow field.

The atomization process can be divided in to two stages: Primary breakup and Secondary breakup. The liquid sheet get disintegrated into first ligament and then in to droplets by aerodynamic action between air and liquid sheet, is called primary breakup. The liquid droplets are evaluated by secondary breakup, drag and collision/coalescence.

The Linearized Instability Sheet Atomization (LISA) Model is most suitable for liquid sheet coming out from pressure swirl atomizer and used in present study. Figure 1 shows the primary atomization process. The swirling liquid comes out of exit orifice of diameter d_0 and makes a liquid film of thickness h_0 at an angle θ. Liquid sheet get disintegrated in to ligaments and further in to droplets. The process can be expressed by equation 1.

$$\dot{m} = \pi \rho_P u h_0 (d_0 - h_0) \qquad (1)$$

As liquid film comes out of the atomizer, it further break up into ligaments because of aerodynamic instability. Senecal et al. [5] developed a model for two dimensional, viscous incompressible liquid sheet moving in incompressible gas medium. A spectrum of infinitesimal disturbances is applied on steadily moving liquid film, in terms of wave amplitude. The most probable droplet diameter that is formed from the ligaments is determined from:

$$d_p = 1.88 d_l (1 + 3Oh)^{1/6} \qquad (2)$$

Where d_l is diameter of ligament, which is formed from liquid sheet and depends on type of wave – short or long. Using the droplet diameter size factor 1.88 and Oh is the particle Ohnesorge number that is defined as:

$$Oh = \frac{\sqrt{We_p}}{Re_p} \qquad (3)$$

Where We_p is the Weber Number based on half the film thickness and the gas density. Re_p is the Reynolds Number based on the slip velocity.

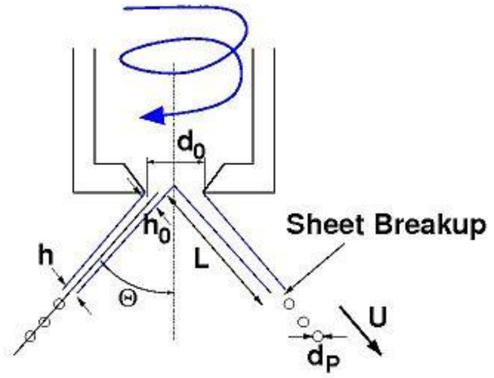


Figure 1. Primary Atomization Process [3]

Secondary Breakup Model

The secondary breakup of the liquid sheet is caused by turbulence within the liquid phase, implosion of cavitation bubbles and external aerodynamic forces acting on the liquid sheet. Breakup regime typically may classified by Weber number of liquid phase.

$$We = \rho V^2 D/\sigma \qquad (4)$$

If a droplet is exposed to a gas flow, significant deformation starts at a Weber number of unity. Above a certain value of the Weber number, the droplet deformation leads to breakup. Typically, the following breakup regimes are observed and shown in figure 2 [1]:

Vibrational breakup: We < 12

Bag breakup: 12 < We < 50

Bag-and-stamen breakup: 50 < We < 100

Sheet stripping: 100 < We < 350

Catastrophic breakup: 350 < We

For the numerical simulation of droplet breakup, a statistical breakup approached is used. It is assumed that if a droplet breaks up into child droplets, the particle diameter is decreased accordingly to the predictions of the used breakup model. Stochastic Secondary Droplet (SSD) model is used for present study.

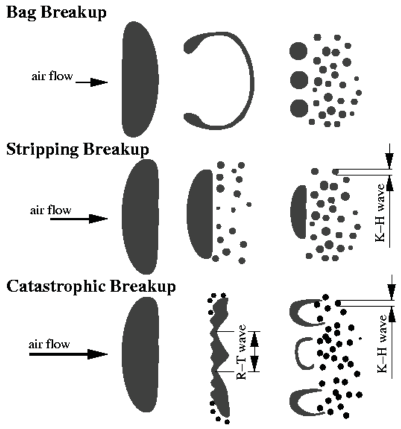


Figure 2. Types of Secondary Breakup [1]

Stochastic Secondary Droplet (SSD) Model

In combustion application atomization process is affected by turbulence [6], droplet collision [7], cavitating flow inside nozzle [1] etc. and further it may result in large spectrum of droplet size. SSD model can capture these large number of droplets.

Kolmogorov [8]'s stochastic theory suggest the probability of breakup of parent particle in to number of child particles does not depend on parent particle size. Further theoretical developments of Kolmogorov's stochastic theory can be found in Gorokhovski and Saveliev [9]. The Kolmogorov's hypothesis is reformulated in the differential term by Fokker – Planck equation [10].

If the initial diameter of the parcels is known, properties of new droplets, number of droplets and breakup time can be predicted by selected breakup model. The critical radius of parcel is:

$$r_c = \frac{We_c \sigma_p}{\rho_g u_{rel}^2} \qquad (5)$$

The parcels with radius larger than critical radius are subjected to breakup and the breakup time is defined as

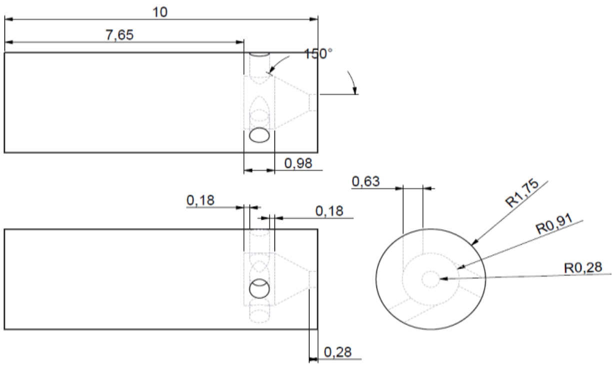
$$t_{bu} = B \sqrt{\frac{\rho_p}{\rho_g}} \frac{r}{|u_{rel}|} \qquad (6)$$

Where B is the user-specified breakup constant. When a parcel reaches breakup, it is destroyed and new parcels are created. The diameters of these child parcels are obtained by sampling a distribution function in the log of the diameter, x = ln(r):

$$T(x) = \frac{1}{\sqrt{2\pi\langle\xi^2\rangle}} exp\left[\frac{-(x - x_0 - \langle\xi\rangle)^2}{2\langle\xi^2\rangle}\right] \qquad (7)$$

where $<\xi>$ and $<\xi^2>$ are parameters of the model. When breakup occurs, parent parcels are destroyed and new parcels are created. The number of drops represented by each parcel is approximately equal to a target number in the parcel (NP). This continues until the mass of the parent parcel is used up. A scaling factor is then applied to the number of drops in all the new parcels to conserve the mass of the parent parcel.

Figure 3 shows the dimensional drawing of the pressure swirl atomizer under study. In the present work commercially available CFD tool ANSYS – Fluent is used. The Primary breakup is carried out using LISA model which is best suited for pressure swirl atomizer. The secondary breakup is analysed by SSD breakup model. The Sautar Mean Diameter (SMD) is plotted. The geometrical fluid model is developed based on designed dimensions. Figure 4 shows the geometry under analysis and showing boundaries.



(a) Inner part of Atomizer (b) Outer part of Atomizer

Figure 3. Dimensional Drawing of Pressure Swirl Atomizer (All dimensions are in mm)

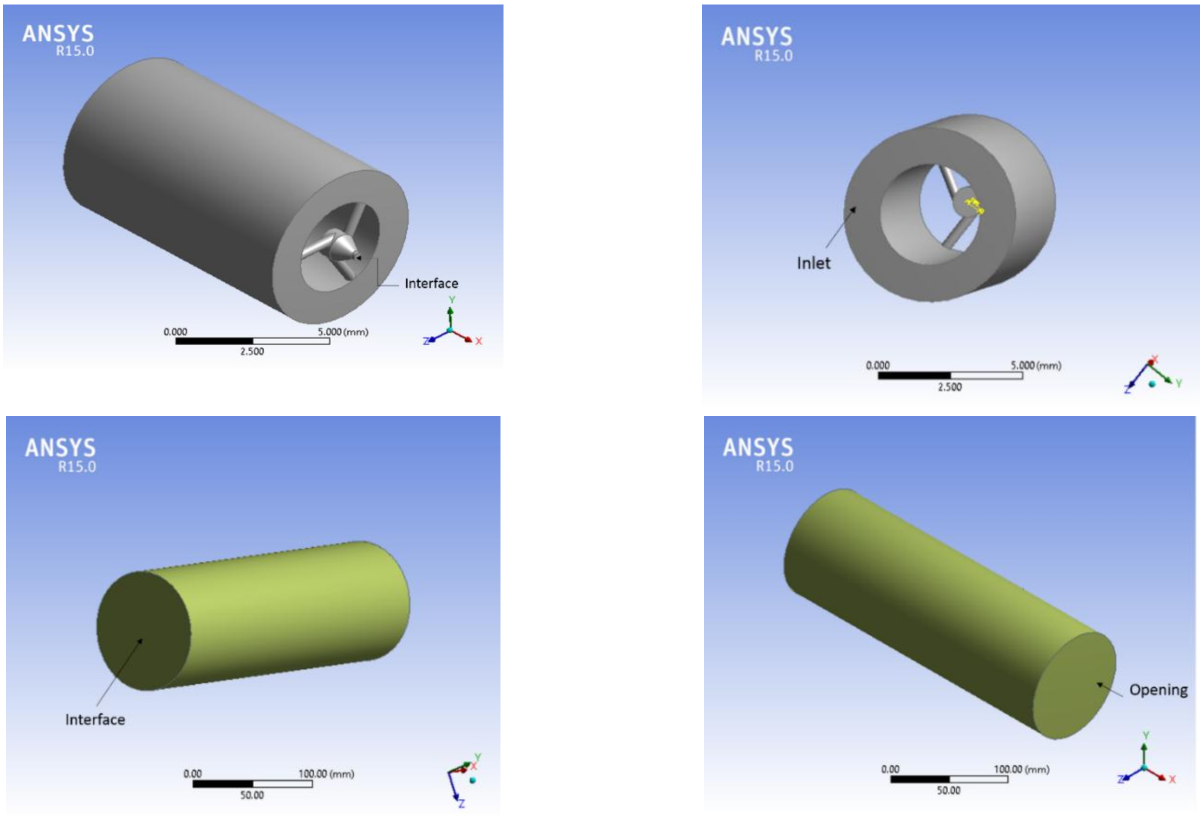


Figure 4. Nozzle and Spray Chamber Geometry

The grid independent study has been carried out for the present geometry of the pressure swirl atomizer. The unstructured mesh with tetrahedral elements are used. The meshing has been started with coarse mesh having 167515 number of tetrahedral elements. The Sauter Mean Diameter is measured for 6 bar injection pressure. The number of tetrahedral elements are increased by changing minimum size of the elements in mesh size setting. It has been found that after 232318 elements, decreasing mesh size do not change SMD and it is shown in figure 5.

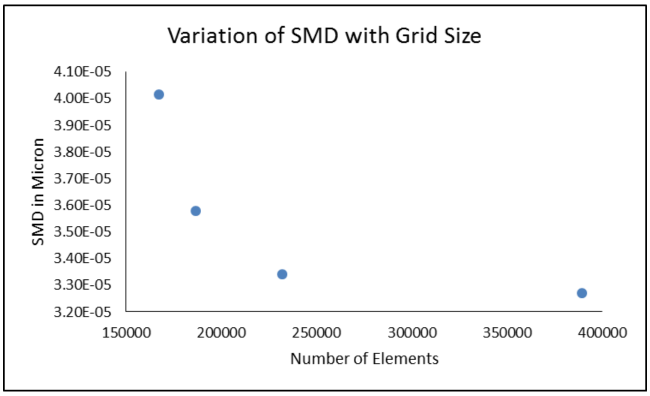


Figure 5. Grid Independence Study

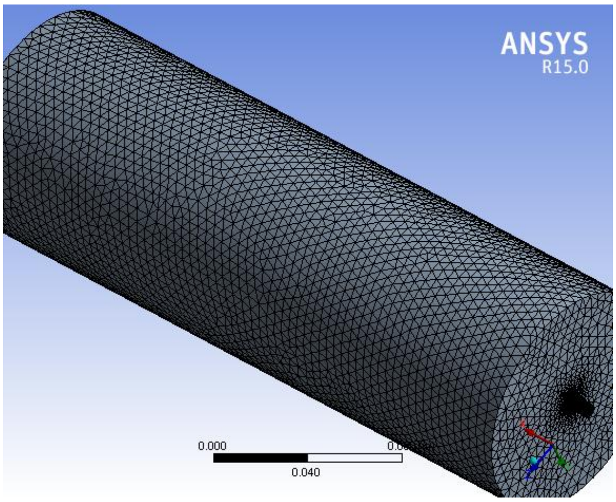


Figure 6. Generated Mesh

Figure 6 shows the meshing of the fluid domain under analysis. The 3D analysis the object is carried out. In general setting of fluent Pressure Based, Steady State Solver is selected. In Model option, energy equation is kept on. The realizable k-ε turbulence model with standard wall function is selected to define turbulence for the problem. The species transport and dispersed phase model is kept on.

Ethyl alcohol - air mixture is selected for vapor phase material and ethyl alcohol – liquid is selected as droplet material. In dispersed phase unsteady particle tracking is selected with particle time step size of 0.0001 s. The injection parameters are set for pressure swirl atomizer which uses LISA model for primary breakup. For secondary breakup TAB model is selected with dynamic drag law. The injection pressure is set to 6 bar, 9 bar, 12 bar, 15 bar and 18 bar.

THEORETICAL APPROACH

In pressure swirl atomizer, the drop size relations are determined by empirical methods because of complexity of various physical phenomena are involved in atomization process from pressure swirl atomizer. The correlations for mean drop size of the form

$$SMD = \sigma^a \upsilon^b \dot{m}_L^c \Delta P_L^d \tag{8}$$

From the above, empirical equation derived by Radcliffe [11] and subsequent work carried by Jasuja [12] and Lefebvre [13] yield similar equation. Ballester [14] gave empirical equation that include the geometrical parameter that affect the atomization.

Wang and Lefebvre [15] proposed an equation based on physical principle of pressure-swirl atomizers. The formation of the droplets depends on the absolute velocity of the liquid and the relative velocity between the liquid and the gas. Squire [16], Chu [17], Dombriwoski and Jone [18], Counto [19] had also contributed in the development of empirical equation of SMD based on liquid sheet instability. Table 1 shows the empirical equations available in literature and used for comparison with numerical results.

Table 1. Empirical equations of SMD for Pressure Swirl Atomizer

$SMD = 7.3\dfrac{\sigma^{0.6}{\mu_L}^{0.2}\dot{m}_L^{0.25}}{{\rho_L}^{-0.2}\Delta P_L^{-0.4}}$	Radcliffe
$SMD = 4.4\dfrac{\sigma^{0.6}{\mu_L}^{0.16}\dot{m}_L^{0.22}}{{\rho_L}^{-0.16}\Delta {P_L}^{-0.43}}$	Jasuja
$SMD = 2.25\left(\dfrac{\sigma\mu_L\dot{m}_L}{\rho_A\Delta P_L^2}\right)^{0.25}$	Lefebvre

$SMD = 0.436\left(\dfrac{\mu_L^{0.55}}{P_L^{0.74}d_0^{0.05}A_P^{0.24}}\right)$	Ballester
$SMD = 4.52\left(\dfrac{\sigma{\mu_L}^2}{\rho_A\Delta P_L^2}\right)^{0.25}(tcos\theta)^{0.25}$ $+0.39(\dfrac{\sigma\rho_L}{\rho_A P_L})^{0.25}(tcos\theta)^{0.75}$	Wang & Lefebvre

RESULTS

From the above theoretical correlation, SMD is calculated by fixing the mass flow rate of 1.7259E-4 kg/s and pressure differential of 6, 9, 12, 15 and 18 bar. The exit orifice diameter is 0.56 mm. Liquid ethanol is selected as fluid flowing through an atomizer and air is as continuous medium. The numerical simulation has also been carried out for the same atomizer dimensions and operating parameters using ANSYS – Fluent. LISA model is selected as primary breakup model and SSD model is selected as secondary breakup model.

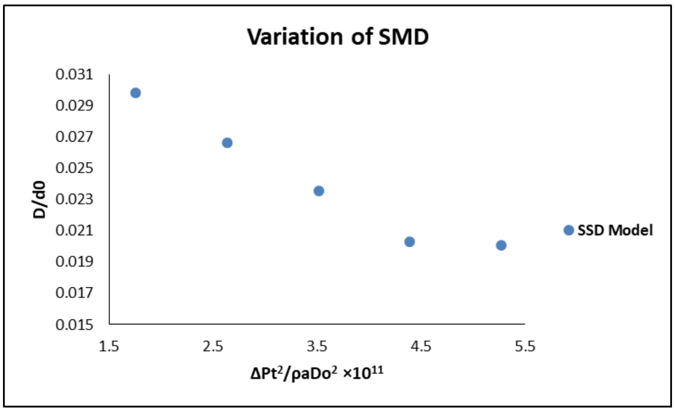


Figure 7. Variation of SMD with Injection Pressure for SSD Model

Figure 7 shows the variation of SMD with injection pressure for SSD model. It shows that as injection pressure increases, the drop diameter decreases, which is an implication of the increase in atomization quality. The increase in the liquid pressure differential causes the liquid to be discharged from the nozzle at a high velocity, which promotes a finer spray. At high flow velocities, the droplet diameter becomes smaller due to increased disturbance on liquid surface.

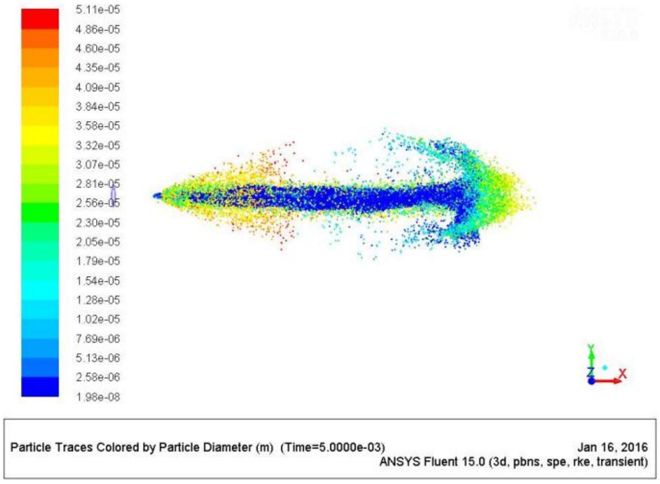


Figure 8. Particle Diameter Track for SSD Model at 6 bar Injection Pressure

Figure 8 shows the particle diameter track at 6 bar injection pressure. Other are shown in Appendix A. Figure 9 shows the comparison of numerical and theoretical results for variation of SMD with injection pressure.

Radcliffe's equation shows the higher value of SMD than other equations. The equation includes only the properties of fuel. The effect of other parameters like atomizer geometry or atmospheric air are not considered while estimating SMD hence the equation under predict than other values. So, the equation is not suitable for SMD prediction for this atomizer and given operating conditions. The Jasuja’s equation give better prediction of SMD than Radcliffe’s equation as the value of exponents and constant in the equation are changed and its accuracy increases as compared to previous one. The Jasuja’s equation cannot predict the SMD accurately as the effect of geometrical parameter is not included in it.

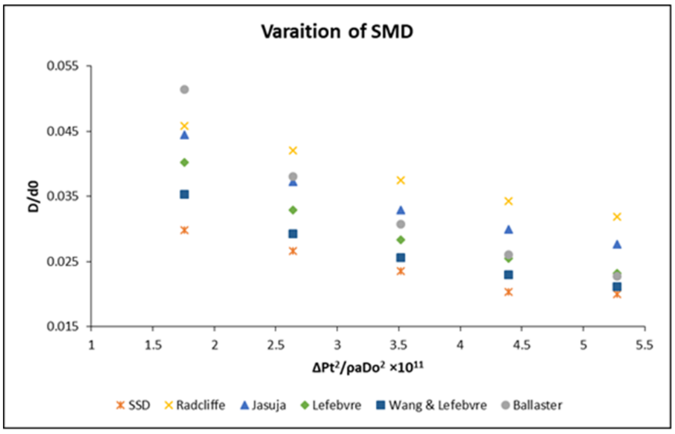


Figure 9. Variation of SMD with Injection Pressure

The Lefebvre’s equation is in better agreement with SSD model then previous equations as it includes the effect of atomizing air. The Wang and Lefebvre equation gives values near to SSD model. All the equations do not include effect of geometrical parameter of nozzle and hence they show higher value of SMD compared to SSD model. The equation given by Ballester includes geometric parameters but ambient conditions is not included therefore not suit7able for combustion application. It is also noted from the figure 9 that at higher injection pressure the difference between Wang and Lefebvre equation and SSD results become negligible.

CONCLUSIONS

The CFD analysis of small scale pressure swirl atomizer has been carried out using ANSYS – Fluent. The ethyl alcohol is used as fuel to atomize. The fuel is injected at 6, 9, 12, 15 and 18 bar in spray chamber at atmospheric condition. LISA model is used as primary breakup model and SSD model is used as secondary breakup model. The results are compared with available empirical equations.

It is observed that as the injection pressure increases the SMD decreases. The same trend has been found for both numerical and theoretical results. It can be also concluded that Radcliffe’s and Jasuja’s equations are not suitable for nozzle used in present study and operating condition. Lefebvre’s empirical relation for SMD shows comparable value with SSD results. Ballaster’s equation is not suitable for this nozzle as it includes geometrical and liquid parameters. The Wang and Lefebvre’s equation gives values very close to SSD value at higher injection pressure.

Nomenclature

A_p =	*Area of Tangential Port of Nozzle*	u =	*Axial Velocity*
B =	*User Specified Breakup Constant*	V_N =	*Velocity in Normal Direction*
D =	*Drop Diameter*	V_{slip} =	*Slip Velocity*
d_o =	*Exit Orifice Diameter*	w =	*Tangential Velocity*
h_0 =	*Liquid Film Thickness*	We =	*Weber Number*
K_v =	*Discharge Coefficient*	We_C =	*Critical Weber Number*
m =	*Mass Flow Rate*	σ =	*Surface Tension*
Oh =	*Ohnesorge Number*	μ =	*Viscosity*
ΔP =	*Injection Differential Pressure*	ρ =	*Density*
Re_p =	*Particle Reynolds Number*	ω =	*Angular Velocity*
r_{parent} =	*Parent Droplet Radius*	θ =	*Spray Angle*
r_{drop} =	*Child Droplet Radius*	**Subscripts**	
r_c =	*Critical Radius of Child Droplet*	A =	*Air*
t =	*Time*	g =	*Gas*
t_{br} =	*Breakup Time*	L =	*Liquid*
U =	*Total Velocity*	p =	*Particle*

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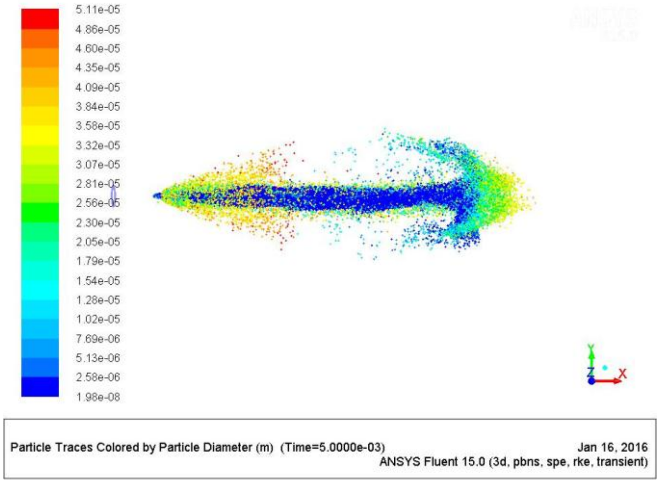
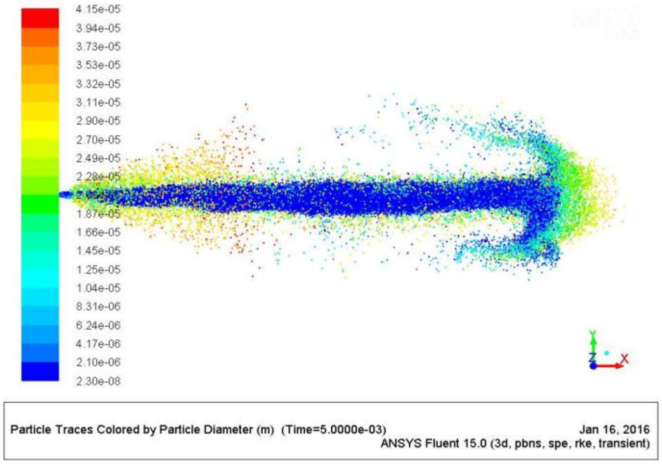
Appendix A

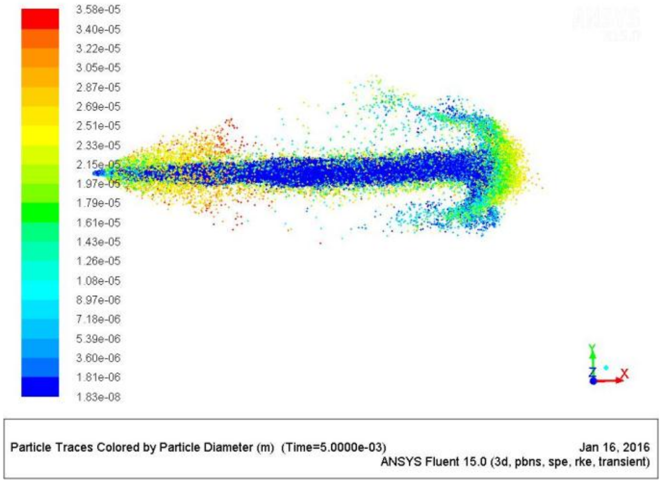
Particle Diameter Track for SSD Model



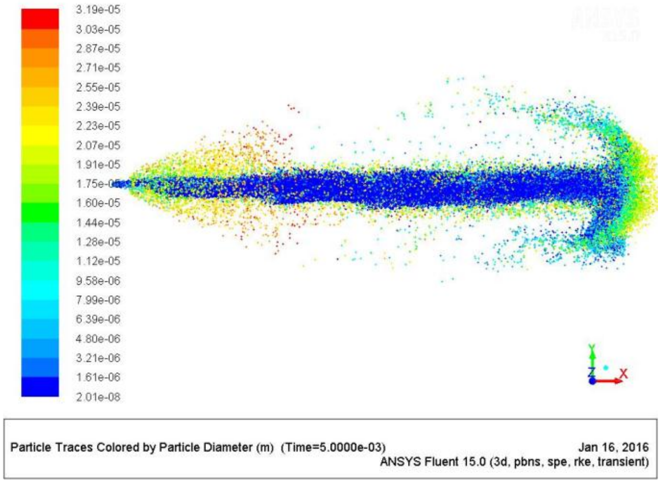
Injection Pressure 6 Bar



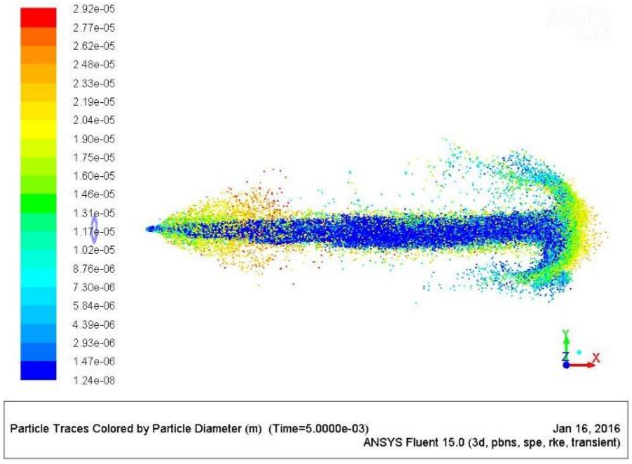
Injection Pressure 9 bar



Injection Pressure 12 bar



Injection Pressure 15 bar



Injection Pressure 18 bar