

FLOW EFFECT DUE TO GEOMETRICAL CHARACTERISTICS OF PRESSURE-SWIRL GDI ATOMIZERS

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ABSTRACT

Gasoline direct injection requires atomisers that are able to comply with stringent requirements in terms of spray structure and mean droplet size. Internal geometrical characteristics of an atomizer play an important role in producing the required spray quality. This paper investigates spray formation and outcome of a pressure-swirl type atomiser with several internal geometrical characteristic configurations using commercially available computational fluid dynamics codes. Both steady and unsteady flow of the spray formation from inside of the final orifice to a few millimeters downstream the nozzle with three different shapes of needle tips as well as two swirl intensities were investigated at fuel-air pressure differential from 3.0 to 10.0 MPa. The calculations took the advantages of fast and low computing cost by applying 2D-axisymmetric swirl solver together with multiphase Eulerian volume of fluid technique. The calculated data were validated by comparing measured static mass flow rate of an actual pressure-swirl atomizer at several fuel-air pressure differentials. Data from the calculations such as mass flow rate, spray cone angle, and liquid sheet thickness at nozzle exit were used to calculate the resultant droplet Sauter mean diameter using a known empirical correlation. Results from the calculations suggest that relatively high fuel-air pressure differential, lower discharge coefficient, stronger swirl intensity, thinner liquid film, and larger spray cone angle produce smaller droplet Sauter mean diameter.

Keywords: Computational Fluid Dynamics (CFD), Gasoline Direct Injection (GDI), Liquid Sheet Thickness, Multiphase Flow, Pressure-swirl Atomizers, Sauter Mean Diameter (SMD), Spray Angle

1. INTRODUCTION

Gasoline Direct Injection (GDI) was proven as a successful approach to reduce automobile exhaust harmful emission and improves fuel economy [1]. Unlike indirect injection gasoline engine, direct injection of liquid gasoline directly into the combustion chamber enables the application of air-fuel mixture stratification technique. Better combustion is achieved by distributing richer air-fuel mixture near the ignition source. Other advantages of GDI engine are better throttle response, possibility of fuel cut-off during acceleration, and rapid combustion stabilisation especially during cold start.

One of the important elements behind the success of GDI in automotive engines is its air-fuel mixture control via fuel atomisers or injectors [2]. Since the fuel is injected directly into the combustion chamber, the time available for the fuel to evaporate before the combustion takes place in each cycle is much lower compared to indirect injection. Due to this particular reason, the resultant spray of GDI atomiser should have a Sauter Mean Diameter (SMD) of less than 20 μm compared to approximately 100 μm for indirect atomiser.

The most popular GI fuel atomizer is the pressure-swirl atomiser or sometimes known by the gas turbine community as the simplex atomiser. The pressure-swirl atomiser is widely preferred by GDI engine developer because of its compact hollow-cone spray that produces fine droplets with increasing fuel-ambient pressure differential, the suppression of spray penetration with the increase of ambient pressure, and a simple yet cost effective construction compared to other types of atomisers. In order to achieve the required mean droplet size and fuel quantity, pressure-swirl atomiser is usually operated with

air-fuel pressure differential between 3.0 to 13.0 MPa with a typical value of 5.0 MPa [1].

Figure 1 shows a classical theory on spray evolution that emerges from the orifice of a pressure-swirl atomiser as described by Lefebvre [3] and Cousins *et al.* [4]. The evolution of the spray as the injection pressure is increased from zero to any pressure mainly consists of five stages, i.e. (i) dribble, (ii) distorted pencil, (iii) onion, (iv) tulip, and (v) atomisation. The discharge coefficient and spray cone angle of the atomiser would differ for each stage until it reaches an asymptote value in the final stage.

The internal geometries of pressure-swirl atomisers have great effect on the resultant spray characteristics [5, 6]. Among the types of pressure-swirl atomisers, variations of its internal geometries are pronounced. The internal geometry of pressure-swirl atomisers mostly varies in terms of final orifice lengths and diameters as well as swirl slots (helical, axial, and tangential). Nevertheless, the geometry of the needle tip remains unstudied with the exception of the work by authors [7].

The importance of pressure-swirl atomizers internal geometries becomes more pronounced when the spray has reached a steady state. Upon reaching a steady state, the discharge coefficient and the spray cone angle of a pressure-swirl atomizer largely depends on its internal geometry and the fluid properties [8, 9]. In addition, the authors [7] also found that the internal geometry affects the resultant liquid sheet thickness downstream of the pressure-swirl atomisers. During unsteady state, the time for the spray to reach the steady state of atomization is critical especially in GDI application where the fuel was injected at high frequency [4]. Therefore, an injector configuration with the least time to reach the stable stage (v) is highly desirable.

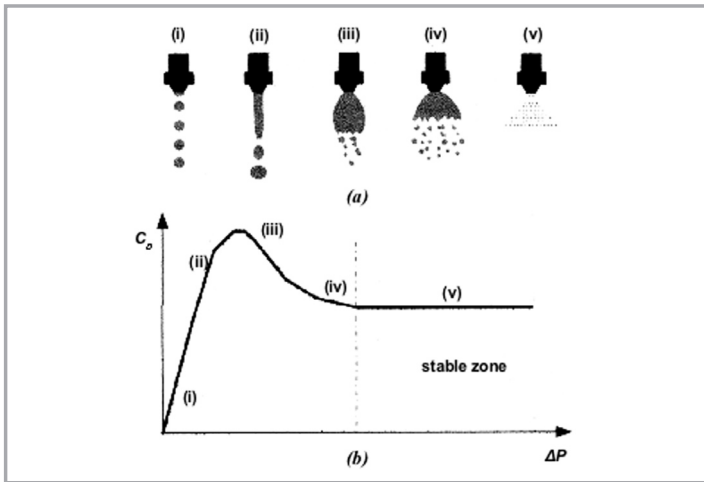


Figure 1: (a) Evolution of liquid structure with injection pressure [3], and (b) Evolution of discharge coefficient for a pressure-swirl atomizer [4]

The objective of this study is to investigate on the effect of geometrical shape of the atomiser needle tip and the angle of tangential swirl slots upon the pressure-swirl atomizer static flow rate, the evolution of discharge coefficient, the spray angle, the liquid sheet thickness at nozzle exit, and the calculated droplet SMD. Regions of interest that depicts the most important unsteady flow would be a few millimeters inside and downstream the final nozzle orifice. However, it is nearly impossible to perform an experiment to study the unsteady flow within these regions. Thus, a Computational Fluid Dynamics (CFD) approach to predict the probable unsteady flow characteristics is highly helpful in understanding the effect of altering several important internal geometries. According to Arcoumanis *et al.* [6], the most suitable technique to represent the actual event is by using 3D volume of fluid multiphase model, which consists of mainly two phases: (i) liquid fuel, and (ii) air. In this study, similar multiphase technique was used but the case studies were simplified into 2D axisymmetric swirl representations.

2. COMPUTATION

The conservation of angular momentum of the axisymmetric 2D swirling flow is governed by [10]:

$$\frac{\partial}{\partial t}(\rho w) + \frac{1}{r^2} \frac{\partial}{\partial x}(r \rho u w) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v w) = \tag{1}$$

$$\frac{1}{r} \frac{\partial}{\partial x} \left(r \mu \frac{\partial w}{\partial x} \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^3 \mu \frac{\partial}{\partial r} \left(\frac{w}{r} \right) \right) - \rho \frac{v w}{r}$$

where x is the axial coordinate, r is the radial coordinate, u is the axial velocity, v is the radial velocity, and w is the tangential velocity.

In an Eulerian multiphase approach, the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of phasic volume fraction is introduced. The volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. These volume fractions, denoted here by ϕ_q , represent the space occupied by each phase, and the laws of conservation of mass and momentum are satisfied by each phase individually. For example, the volume of phase q , V_q , is defined by

$$V_q = \int \phi_q dV \tag{2}$$

where

$$\sum_{q=1}^n \phi_q = 1 \tag{3}$$

The effective density of phase q is

$$\hat{\rho}_q = \phi_q \rho_q \tag{4}$$

where ρ_q is the physical density of phase q .

Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. The general conservation equations from/to which these equations are derived are too lengthy to be discussed here. Such information can be found in [10].

The CFD codes used in this work is *Fluent 6.1* due to software availability and function adequacy. The internal nozzle geometry similar to a *Mitsubishi GDI* atomiser was arbitrarily selected as a base case study. A simplified cross-section of such atomizer is shown in Figure 2(a). This study computes the unsteady formation of liquid fuel emerging from the geometrically similar pressure-swirl atomizer except for three variations of needle valve tips, and two different swirl intensities. The region of particular interest is shown in Figure 2(b), where the swirling motion of the liquid fuel initiated and ended with atomization just downstream the final orifice. The studied atomiser can be generally categorised as follows:

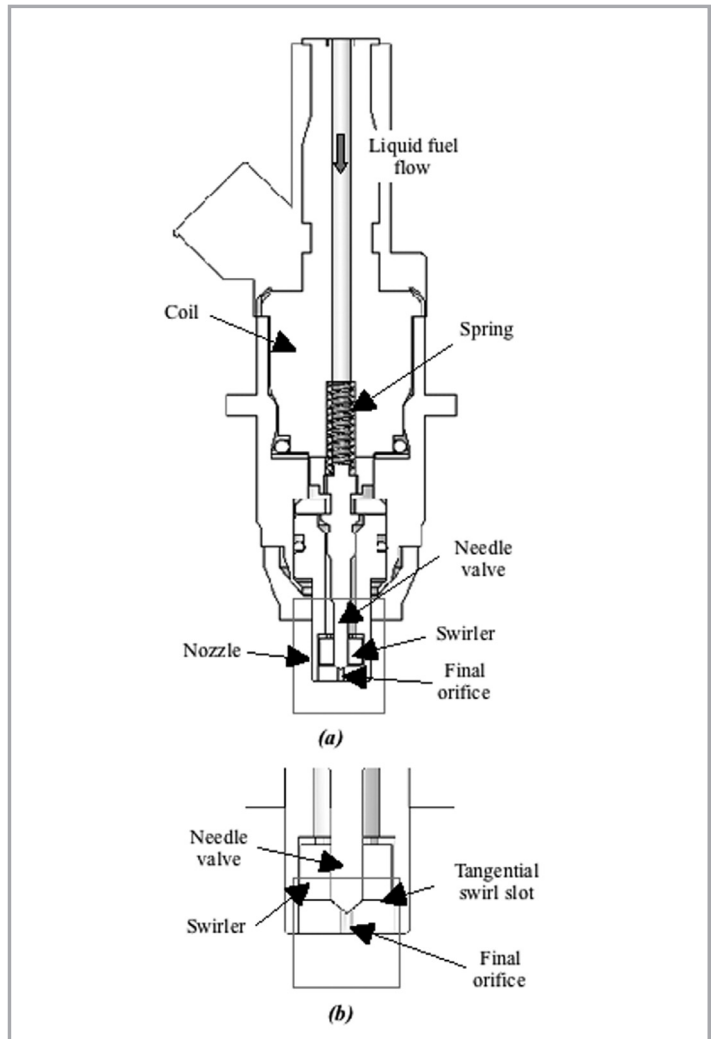


Figure 2: (a) Cross-section of a GDI injector, and (b) geometrical region that has great influence on the spray characteristics

- a) Atomization approach: high-pressure, swirl, single fluid,
- b) Actuating mechanism: electromagnetic (solenoid),
- c) Nozzle opening: inwardly,
- d) Swirl generator: tangential slots,
- e) No. of holes: single,
- f) Spray pattern: hollow-cone.

The flow inside the pressure-swirl atomiser and its near nozzle vicinity can be simplified into two phases: (i) liquid fuel, and (ii) air. In this study, an Eulerian multiphase model was used with n-Heptane representing the liquid fuel. The internal flow was calculated with the following assumptions:

- a) the ambient air is initially quiescent,
- b) the transient effect of the needle lift is negligible,
- c) needle lift is at maximum and its distance is constant at 50 μm ,
- d) pressure drop from high pressure fuel line to the injector tangential slot is virtually negligible,
- e) the flow is adiabatic and incompressible,
- f) the flow is fully turbulence and the effects of molecular viscosity are negligible,
- g) all fuel entering the needle seat passage from all the tangential slots has the same vector relative to the axis of symmetry.

Figure 3 shows a representation of fuel inlet vector entering needle seat passage from angled tangential slots, viewed from nozzle exit. It is assumed that all fuel entering the needle seat passage from all the tangential slots has the same vector relative to the axis of symmetry. A single swirl inlet angle a parallel to the tangential slot was chosen to represent each of the swirl intensity investigated. The directional vector components chosen are listed below:

- a) Strong swirl components: axial = 0, radial = -0.617, tangential = -0.787.

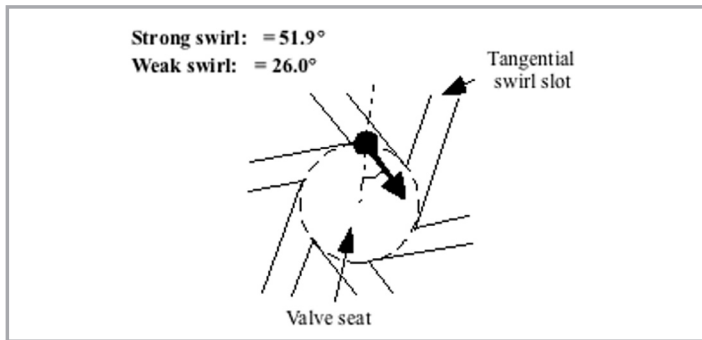


Figure 3: Representation of fuel inlet vector entering needle seat passage from angled tangential slots, viewed from nozzle exit

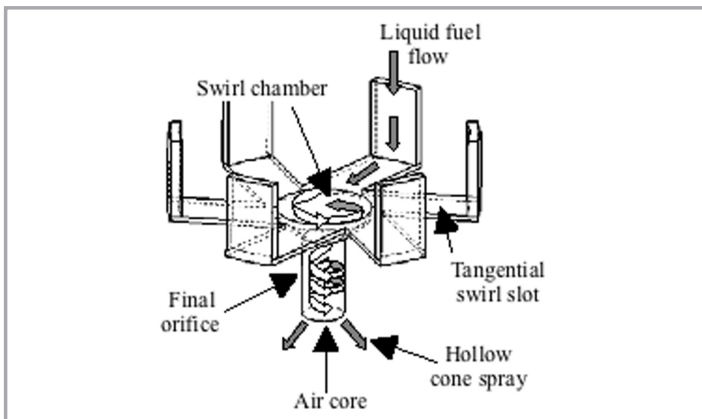


Figure 4: Volume of fluid of the tangential swirl slots, swirl chamber, and final orifice

- b) Weak swirl components: axial = 0, radial = -0.899, tangential = -0.438.

The above assumption allows the application of 2D axisymmetric swirl solver, which greatly reduces the computing cost. The calculation domain, which is represented as a 3D volume of fluid shown in Figure 4, is therefore simplified into a 2D region shown in Figure 5. The 2D region consists of only three sections: (i) valve seat passage, (ii) final orifice, and (iii) a few millimeters downstream the nozzle exit.

All six configurations studied are shown in Table 1. For each configuration, a computation was done for fuel/ambient pressure differential from 3.0 MPa to 10.0 MPa with a step size of 0.5 MPa. The renormalisation group (RNG) $k-\epsilon$ turbulence model was chosen for this study due to several considerations such as [11]:

- a) Extends the $k-\epsilon$ turbulence model with strong theoretical basis of determining constants without empiricism,
- b) Computationally more robust than standard $k-\epsilon$ model, plus its ability to replace wall function with a fine grid,
- c) Compared with standard $k-\epsilon$ model, the RNG model is more accurate for separated flow, stagnation point flow and swirling flow.

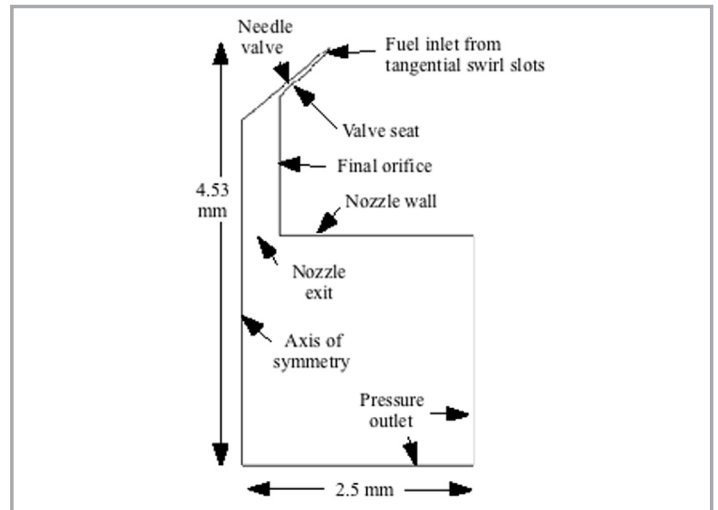







Figure 5: Boundaries of the 2D rotating region for configuration A and D (point tip needle)

The 2D rotating surfaces for each case were meshed using a scheme size of 0.05 mm. With this scheme size, the resulting number of cells for each case is approximately 3,000 cells. The minimum and maximum face areas were approximately $0.2 \times 10^{-3} \text{ mm}^2$ and $1.0 \times 10^{-3} \text{ mm}^2$ respectively. Then, the grid was a further refined using solution-adaptive refinement feature. After refinement, the number of cells for each case increased to 11,000 cells approximately. The final minimum and maximum area of the faces were closing to $0.2 \times 10^{-6} \text{ mm}^2$ and $1.0 \times 10^{-6} \text{ mm}^2$ respectively. The mesh density values were selected after several calculation attempts as a trade-off between accuracy and computing cost.

3. RESULTS AND DISCUSSION

The validation of the calculation was done by measuring the static flow rate of a Mitsubishi GDI pressure-swirl atomizer at fuel-ambient pressure differential from 3.0 MPa to 10.0 MPa, with a step size of 1.0 MPa. The methodology applied for measuring the static flow rate was adapted from SAEJ1832 [12]. The result of the measurement and the result from the calculation

Table 1: Case study configurations

Config-uration	Needle valve tip			Swirl intensit	
	Point 	Extrude 	Round 	Strong 	Weak 
A					
B					
C					
D					
E					
F					

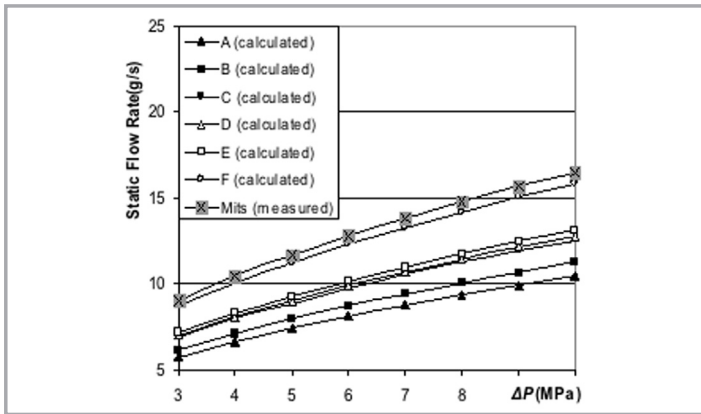


Figure 6: Calculated and measured static mass flow rate of several atomizer configurations

made under similar condition are shown on Figure 6. It can be seen that all the calculated values showed lower static flow rate compared to the actual measurement. Such difference maybe caused by the fuel flowing through the narrow gap between the needle valve and its guide that is not considered in these calculations. Although the calculated mass flow rates are about 6 % to 48 % lower than the measured value, the overall trend is the same and the discrepancy is consistent through the investigated pressure differential ranges.

The steady state phase contour of the CFD calculation is shown in Figure 7. It was observed that in this calculation, the thin liquid sheet has fully developed and reached its steady state in less than 0.16 ms after Start of Injection (SOI). However, the analysis was arbitrarily done with data taken at 0.32 ms after SOI.

From the results, half cone spray angles, ϕ for each case were calculated. The spray angle of pressure-swirl atomizers is defined

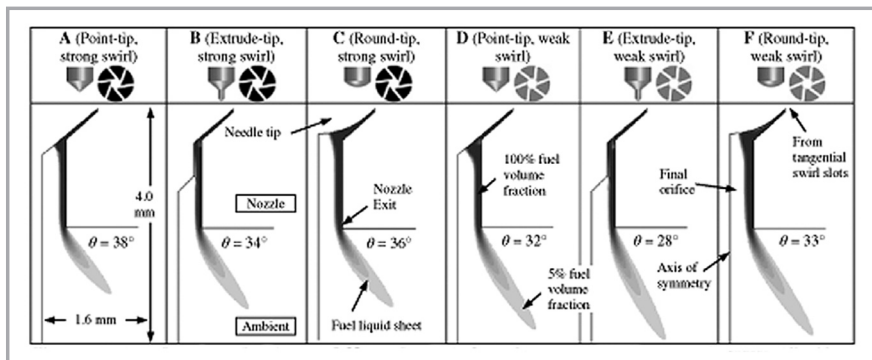


Figure 7: Volume fraction of liquid fuel at 0.32ms after SOI, plotted in grayscale. The color black represent liquid fuel volume fraction 100%

by evaluating fuel velocity components exiting the nozzle [3]. The half cone spray angle, ϕ is given by

$$\phi = C_{\phi} \arctan \left(\frac{w}{u} \right) \tag{5}$$

where C_{ϕ} is the correction factor which is slightly less than 1, w is the tangential velocity component, and u is the axial velocity component. From the work of Ren *et al.* [13], the radial velocity was found to be negligible.

The axial and tangential velocity components were calculated using Cousin *et al.* [4] approach. The mean axial velocity, u is estimated from the value of mass flow rate, m and radius of air core, r_{ac} deduced from CFD calculations at each time step. Here, liquid is assumed to be discharged from the estimated liquid sheet only:

$$u = \frac{\dot{m}}{\pi \rho (r_0^2 - r_{ac}^2)} \tag{6}$$

The mean tangential velocity, w is deduced with respect to the chamber axis:

$$w = \frac{2}{(r_0 + r_{ac})} \frac{\sum_{i=1}^n r_i w_i}{n} \tag{7}$$

where r_i and w_i correspond to the values of the radius of the orifice and the tangential velocity on the n nodes along a radius of the orifice at nozzle exit where the liquid sheet is assumed to be present. It was found that when it reached a steady state, the resulting spray cone angle remains virtually unchanged for each case throughout the ranges of pressure differentials applied. Such trend showed similarity with calculations and measurements made by Ren *et al.* [13] to study the influence of pressure differential on spray cone angle. Thus, the spray angle for each case is considered constant throughout the fuel-air pressure differentials from 3.0 MPa to 10.0 MPa.

The effect of each case study on the discharge coefficient is shown in Figure 8. All the trends show much similarity with the Lefevbre [3] classical theory, except between stage (iii) and (iv). For all these cases, the discharge coefficient between (iii) and (iv) shows a large fluctuation. However, the configuration with low swirl strength showed more stable fluctuation of discharge coefficient between stages (iii) to (iv). As far as needle shape is concerned, surprisingly the extrude-tip needle showed the shortest time to reach the atomization stable stage (v), while the round-tip needle showed the largest discharge coefficient fluctuation in stage (iii) and (iv). Nevertheless, to validate this result with actual transient measurement may not be possible because such instantaneous mass flow rate measurement would not be possible even with the latest measuring device. Although this result may not be supported by any experimental work, it still would give a good insight of such phenomena.

Figure 9 shows the liquid film thickness at nozzle exit for each case configuration. The sheet thicknesses were obtained from CFD output data of volume fraction of liquid fuel, where 50% volume fraction was taken as a borderline

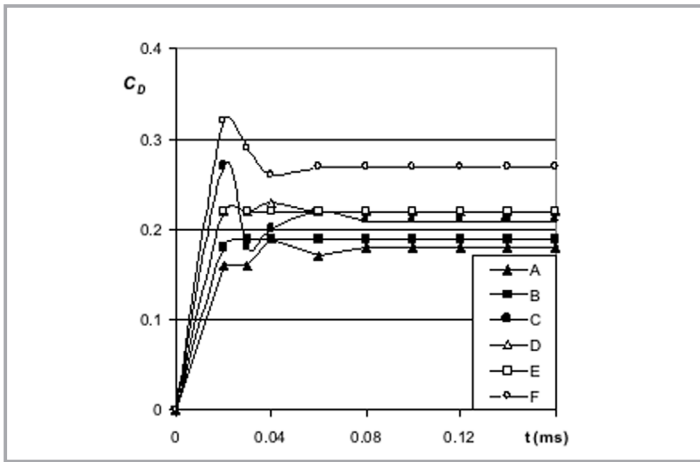


Figure 8: Effect of several combinations of needle-tip shape and swirl intensity on discharge coefficient

between the phases of liquid and gas. Also included in the figure is a related empirical correlation of pressure-swirl atomizer liquid sheet thickness found by Suyari and Lefebvre [14]. The correlation is given by

$$t_f = 2.7 \left(\frac{d_0 \dot{m}_L \mu_L}{\Delta P \rho_L} \right)^{0.25} \quad (8)$$

The data of liquid sheet thickness from CFD calculation showed relatively good agreement with Suyari-Lefebvre correlation for a pressure-swirl injector static flow of 900 cc/min rated at 5.0 MPa. Although Suyari-Lefebvre correlation is fairly simple and failed to describe any effect of injector needle shape and swirl intensity, all the liquid sheet thickness relation with fuel-air pressure differential show similar trend.

Next, the theoretical droplet SMDs were calculated from liquid sheet thicknesses and half spray cone angles obtained from the CFD calculations. The result for each case configuration is shown in Figure 10. The theoretical droplet SMD were calculated using Wang-Lefebvre SMD correlation [15], which is given by

$$\text{SMD} = 4.52 \left(\frac{d_0 \dot{m}_L \mu_L}{\Delta P \rho_L} \right)^{0.25} (t_f \cos \phi)^{0.25} + 0.39 \left(\frac{\sigma \mu_L^2}{\rho_A \Delta P^2} \right)^{0.25} (t_f \cos \phi)^{0.25} \quad (9)$$

From Figure 10, theoretical droplet SMD showed significant reduction with relatively high swirl intensity regardless any needle-tip geometrical shapes. Under similar swirl strength influence, point-tip needle produces finer droplet SMD followed by extrude-tip and round-tip in that particular order throughout all tested pressure differential range. Another interesting point, the calculated droplet SMD for point-tip needle is less than extrude-tip needle throughout the investigated pressure differentials although the data for liquid sheet thickness for such needle geometrical shape (Figure 9) shows otherwise. This occurrence would suggest that the spray angle for pressure-swirl atomizer is a relatively more important factor than the liquid sheet thickness in determining the resultant droplet SMD.

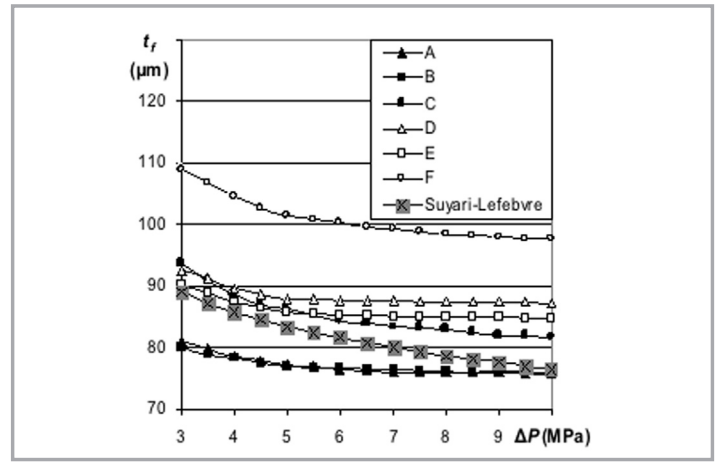


Figure 9: Liquid sheet thickness, t_f at Nozzle Exit of each case configuration with pressure differential, ΔP ranges from 3.0 to 10.0 MPa

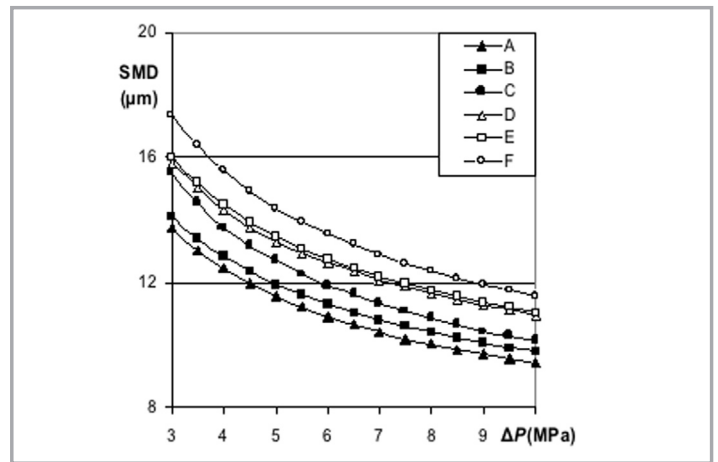


Figure 10: Theoretical droplet SMD calculated using Wang-Lefebvre correlation given by Equation (9) with liquid sheet thickness and spray cone angle obtained from CFD calculations.

4. CONCLUSIONS

This investigation was about comparing three types of needle geometry of pressure-swirl atomizers with two different swirl intensities. The study was done using CFD at fuel-air pressure differential from 3.0 to 10.0 MPa with a step size of 0.5 MPa. From the result obtained, several conclusions can be made:

- The use of 2D axisymmetric swirl multiphase Eulerian enables rapid and adequate CFD calculation of the internal flow and near nozzle vicinity of pressure-swirl atomizers.
- Results from the calculations suggest that relatively high fuel-air pressure differential, lower discharge coefficient, stronger swirl intensity, thinner liquid film, and larger cone angle produce better atomization.
- Needle-tip geometry either alone or mated with swirl strength does affect atomization by means of influencing the resulting discharge coefficient, liquid film thickness and the spray cone angle.
- At fuel-air pressure differential ranging from 3.0 to 10.0 MPa, point-tip needle combined with high swirl intensity generally produce lowest discharge coefficient, thinner liquid film, larger spray cone angle, and smaller droplet size than extrude-tip and round-tip needle.
- The extrude-tip needle showed the shortest time in reaching the spray stable zone (v), which indicates an excellent advantage in the application of short spray pulse width.

f) Needle tip geometrical shape and swirl generator configuration should be a considerable factor in designing fuel injectors especially for GDI application.

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LATIN SYMBOLS

A	=	point-tip needle; strong swirl (-)
B	=	extrude-tip needle; strong swirl (-)
C	=	round-tip needle; strong swirl (-)
D	=	point-tip needle; weak swirl (-)
E	=	extrude-tip needle; weak swirl (-)
F	=	round-tip needle; weak swirl (-)
d_0	=	final orifice diameter (mm)
k	=	turbulence kinetic energy (m^2/s^2)
m_L	=	mass flow rate (g/s)
t_f	=	thickness of liquid film at nozzle exit (μm)
t	=	time (ms)

GREEK SYMBOLS

α	=	swirl inlet angle ($^\circ$)
ΔP	=	pressure differential between liquid fuel and ambient (MPa)
ε	=	turbulence dissipation rate (m^2/s^3)
μ_L	=	liquid fuel viscosity (Ns/m ²)
ρ_A	=	ambient air density (kg/m ³)
ρ_L	=	liquid fuel density (kg/m ³)
σ	=	surface tension (J/m ²)
θ	=	half spray cone angle ($^\circ$)

PROFILES



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