Effect of Inlet Slot Number on the Spray Cone Angle and Discharge Coefficient of Swirl Atomizer

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Abstract

Liquid atomization is a process of changing the liquid into small droplets. There are many applications which are related to liquid atomization including fuel injection in combustion systems and also in agricultural sprays. In pressure swirl atomizer, the liquid is injected into the atomizer through tangential port and a swirling motion is formed inside the swirl chamber. At high strength of swirling motion, an air core will be visible inside the atomizer. The liquid is then discharged from the orifice to form a spray which breaks up the liquid into small droplets. The objective of this paper is to report on the effect of inlet slot number (n) on the spray cone angle and discharge coefficient (C_d). The injection pressure was varied in the range of 2 to 8 bar and water was used as the working fluid. Experimental data shows that the spray cone angle increases as the injection pressure increased, regardless of inlet slot number. It is also observed that the atomizer with the most number of inlet slots produces widest spray. The effect of injection pressure on spray cone angle is more prominent at a lower range of injection pressure and greater number of inlet slot. The spray cone angle increases by only 5.4% as the inlet slot number increased from 2 to 5 for an injection pressure of 2 bar, but increases by 10.7% for an injection pressure of 8 bar. Furthermore, it is found that higher injection pressure and lesser number of inlet slot leads to lower discharge coefficient. It also noticed that, greater number of inlet slot has higher discharge coefficient.

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Keywords: Pressure swirl atomizer; spray cone angle; discharge coefficient; cold flow test.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ao</td>
<td>Cross sectional area of nozzle orifice</td>
<td></td>
</tr>
<tr>
<td>A_p</td>
<td>Cross sectional area of inlet slot</td>
<td></td>
</tr>
<tr>
<td>C_d</td>
<td>Discharge coefficient</td>
<td></td>
</tr>
<tr>
<td>D_o</td>
<td>Orifice diameter</td>
<td></td>
</tr>
<tr>
<td>D_s</td>
<td>Swirl chamber diameter</td>
<td></td>
</tr>
<tr>
<td>L_s</td>
<td>Length of swirl chamber</td>
<td></td>
</tr>
<tr>
<td>L_o</td>
<td>Length of orifice</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Number of inlet slot</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Flow rate</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Radius of swirl chamber</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>Reynold number</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>Average axial velocity at nozzle inlet (Q/πR^2)</td>
<td></td>
</tr>
</tbody>
</table>

Greek symbols:

- μ: Viscosity
- ρ: Density
- α: Convergent angle of swirl chamber

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1. Introduction

Pressure swirl atomizer is used for liquid atomization in many industries. Liquid atomization is a process to change any liquid to droplets and this is at many applications including fuel injection in combustion systems, spray dispersion of consumer products, manufacturing of pharmaceutical products, detergent and food drying in process industries, and also in agricultural sprays [1]. Atomization characteristics are normally reflected by the spray discharge coefficient. The discharge coefficient \( C_d \) is defined as the ratio between actual and theoretical flow as in Equation (1). The actual discharge is the discharge that occurs and which is affected by friction as the flow passes through the orifice. The theoretical discharge would be the discharge achieved without friction. The coefficient of discharge is heavily related to the volumetric flow rate of the fluid flow and the cross sectional area of the orifice. For well designed injector, the coefficient is very close to unity at high Reynolds numbers [2]. Reynolds number can be express as Equation (2).

\[
C_d = \frac{Q}{A_o \left( \frac{2 \Delta \rho}{\rho} \right)^{\frac{1}{3}}}
\]

\[
Re = \frac{\rho U D_o}{\mu}
\]

The research on discharge coefficient was previously carried out by Hamid et al. [3]. They found that the value of discharge coefficient, \( C_d \) increased with an increase in Reynolds number (\( Re \)) for hollow cone nozzle and solid cone nozzle but after \( Re > 3000 \) the value of \( C_d \) remained constant at 0.6.

The number of inlet slots (also called tangential port) has a direct effect on spray characteristics. Yule et al. [4] had made research on spray characteristic at different number of inlet slots. They found that the atomizer with two inlet slots produces smaller droplet size than single inlet atomizer with same value of cross sectional inlet slot area (\( A_o \)). Another research on the effect of inlet slot number to spray cone angle also was done by Hamid et al. [5]. Their results show that atomizer with the most of inlet slots (six inlets) produces widest spray cone angle compared with the other atomizers. The spray cone angle is a measure of dispersion quality affecting spray penetration, ignition, combustion stability, and emission level [6].

The experimental reported here evaluates the performance of designed pressure swirl atomizer with various geometry of inlet slot number and compares it with the previously mentioned findings of other researchers. The investigations are based on spray cone angle and discharge coefficient (\( C_d \)).

2. Experimental Apparatus and Setup

2.1. Pressure Swirl Atomizer

The effect of geometric parameters on the characteristics of the liquid sheet emanating from the atomizer is extremely important in the design of swirl atomizer. The geometrical parameters of the atomizer includes length of swirl chamber (\( L_s \)), length of orifice (\( L_o \)), diameter of swirl chamber (\( D_s \)), diameter of orifice (\( D_o \)), number of inlet slot, swirl chamber convergent angle (\( \alpha \)), and etc. The schematic geometry of pressure swirl atomizer that is used in cold flow test is show in Fig 1.

![Fig. 1. Schematic geometry of pressure swirl atomizer with 2 inlet slot.](image)

In this experiment, the number of inlet slot is varied between 2 (atomizer D) and 5 (atomizer A). The geometrical dimensions of the atomizers are given in Table 1. Two main characteristics of resulting spray has been measured, i.e. the...
spray cone angle and the discharge coefficient. Perspex has been used to fabricate the atomizers to permit the internal flow visual observation.

<table>
<thead>
<tr>
<th>Geometrical parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swirl chamber diameter, $D_s$ (mm)</td>
<td>40</td>
</tr>
<tr>
<td>Inlet slot diameter, $D_p$ (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Length of swirl chamber, $L_s$ (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Length of discharge orifice, $L_o$ (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Discharge orifice diameter, $D_o$ (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Convergent angle, $\alpha$ (Deg)</td>
<td>30°</td>
</tr>
<tr>
<td>Number of inlet slot, $n$</td>
<td>5,4,3,2</td>
</tr>
</tbody>
</table>

2.2. Cold Flow Test Rig

An experimental test rig was constructed to measure that characteristic of sprays (Fig. 2). All atomizers were tested using water at room temperature as the simulation fluid to investigate the spray cone angle and the discharge coefficient at different injection pressure. Water was used as this is the common fluid used by previous researchers [3-5, 7, 8]. First, water tank is fully filled with water. Then it is pumped to the atomizer. The supply water pressure is controlled via a ball valve. The water flow rate ($Q$) and supply pressure is measured by a digital flow meter and a Bourdon-type pressure gauge respectively. The digital flow meter was pre-calibrated by the manufacturer with an accuracy of ±2% of full scale. The injection pressure is varied in the range of 2 to 8 bar to simulate actual working condition of meso-scale rocket injector. The atomizer is located downward on vertical plane at the end of the hoses and the spray is directly injected into the water tank.

![Image of experimental rig](image)

Fig. 2. Schematic of experimental Rig for Cold Flow Test.

Images of the sprays were captured using a 12 megapixels digital camera for measurement purpose. The camera was located 1 meter away from the spray formation. This distance was chosen due to clear images visualization capture by camera and to avoid water vapor from reaching the camera lens. The entire images were magnified by computer using image editing software “ImageJ”, and were examined to obtain the spray cone angle. This software has been used by other researcher [7] for the same reason. The spray cone angle is measured by the angle between two spray boundaries, indicated by two straight lines as shown in Fig 3.

![Image of spray cone angle measurement](image)

Fig. 3. Sample of spray cone angle measurement with designation of fluid dispersion regions 110 mm from the nozzle.
3. Results and Discussion

There were 16 experiments have been carried out to investigate the effect of inlet slot number on the spray cone angle and discharge coefficient of pressure swirl atomizers. The samples of spray formed by atomizer B (4 inlet slots) are visualized in the images presented in Fig 4. It is possible to observe that, a smooth liquid film around a hollow cone was formed at the exit orifice of atomizer. In other word, complete atomization stages for hollow cone sprays were established at 2 bar and above. It can also be observed from the Fig 4 that the length of water sheet ligament decreases as the injection pressure increased. It also notices that increasing injection pressures leads to wider spray cone angle.

![Fig. 4. Samples of photograph taken for atomizer B at an injection pressure of a) 2 bar b) 4 bar c) 6 bar and d) 8 bar.](image)

The relationships between the numbers of inlet slots with spray cone angle for all atomizers are shown in Fig 5. Atomizer A which has the most numbers of inlet slots produces the widest spray cone angle while the atomizer with the least numbers inlet slots produces the narrowest spray, which is in agreement with the work done by [5]. This observation can be attributed to the fact that more inlet slot tends to increase the azimuthal velocity inside the swirl chamber. However, the increment of spray cone angle as the inlet slot number increased becomes less significant at lower injection pressure. For example, the spray cone angle increases by only 5.4% as the inlet slot number increased from 2 to 5 for an injection pressure of 2 bar, but increases by 10.7% for an injection pressure of 8 bar. Furthermore, the variation of spray cone angle with respect to injection pressure shows a almost linear trend for all atomizers at an injection pressure below 6 bar. The graph also shows that an increasing injection pressure leads to wider spray formation for each atomizer tested, which is in agreement with previous works [3-5, 8].

![Fig. 5. Effect of injection pressure and the number of inlet slot on spray cone angle.](image)
Another important atomizer characteristic studied in the current research is discharge coefficient. The values of $C_d$ as a function of the injection pressure are shown in Fig 6 for all atomizers. It can be seen that at an injection pressure between 2 bar and 6 bar, atomizer A, B and C shows a decreasing trend of discharge coefficient as the injection pressure increased.

![Fig. 6. Effect of injection pressure and the number of inlet slot on discharge coefficient.](image)

However, at higher injection pressure, the injection pressure has a little effect on the discharge coefficient. Atomizer D shows similar trend compared to other atomizers, except that its discharge coefficient becomes less dependent with injection pressure at an injection pressure of 4 bar and above. This observation is related to the swirling strength effect within the atomizer. At lower injection pressure, the swirling strength dominates the flow inside the atomizer, which increases the net resistance of flow leaving the atomizer orifice. As a result, discharge coefficient drops. However, as the injection pressure increased, counter weighing effects of increased strength of swirl and its subsequent decay due to friction in the injector results in almost constant values of discharge coefficient with respect to injection pressure. Fig 6 also shows that atomizer with the most number of inlet slot has the highest $C_d$ compared to other atomizer. This is due to the fact that more inlet slot tends to increase the flow Reynolds number (Fig. 7), which in turn will reduce the wall friction offered to the flow.

![Fig. 7. Relationship between injection pressure and Reynold number.](image)

The relationship between Reynolds number and injection pressure is shown in Fig 7. The graph shows an almost linear trend between injection pressures and Reynolds number. It can be observed that an increase in the injection pressure increased the Reynolds number. Atomizer A has higher flow Reynolds number compared with other atomizers. The Reynolds number is proportional with volume flow rate, so it is expected that atomizer with the most number of inlet slots has the highest flow Reynolds number.

### 4. Conclusion

A series of experiments were conducted to investigate the performance of pressure swirl atomizer with different number of inlet slot. The conclusions are as follow:

- Atomizer with greater number of inlet slot produces wider spray and has higher discharge coefficient.
- The effect of injection pressure on spray cone angle and discharge coefficient is more prominent at a lower range of injection pressure.
- Higher injection pressures leads to wider spray cone angle and lower discharge coefficient.
Acknowledgements

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References