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# Characteristics of Hollow Cone Swirl Spray at Various Nozzle Orifice Diameters

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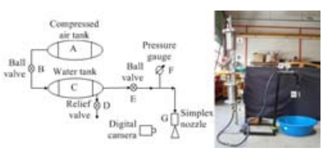
**Graphical abstract**




**Abstract**

An experimental work to investigate the swirl spray characteristics that emanates from hollow-cone and solid-cone spray simplex atomizers is presented. Main objective of the research is to investigate the spray characteristics, i.e. spray breakup length, discharge coefficient and spray cone angle at different nozzle orifice diameter and injection pressure. Discharge coefficient is almost uninfluenced by the operating Reynolds number. This test also reveals that both breakup length and spray cone angle increases as orifice diameter is increased. Higher injection pressure leads to shorter breakup length and wider spray cone angle.

*Keywords*: Simplex nozzle; spray cone angle; discharge coefficient; breakup length



## ■1.0 INTRODUCTION

Simplex nozzles have been applied in many areas including combustion, aerospace propulsion, landscape system, pharmaceutical, agricultural, mining, paint industries and spray flash desalination system. The common objective of the nozzles is to increase liquid surface area to enhance evaporation and distribute a liquid over an area. Simplex nozzles atomize fluid into a flow regime which has been disintegrated into single element in form of fine drop of the working fluid. Most of simplex nozzles work on the same principle; first the pressurized liquid will enter the nozzle at an inlet port. The liquid is then flow out through holes before being forced to flow through several numbers of annular helicoidal slots. The liquid swirls in the swirl chamber. The swirling liquid is finally discharged through a small orifice. The regime of liquid flow forms a cone shaped spray (refer Figure 1).

The understanding of this spray characteristic is important to the revolution of technologies especially with the widespread application of this swirling spray in many areas. This paper summarizes series of simplex nozzle testing that evaluated the swirling spray characteristics with water as the working liquid.

## ■2.0 LITERATURE REVIEW

Xue, Jog, Jeng, Steinthorsson and Benjamin (2004) had numerically investigated the effect of inlet slot angle on spray cone angle and discharge coefficient. They found that an increase in inlet slot angle results in lower discharge coefficient and higher spray cone angle. Other geometrical parameters that will influence the spray characteristics are swirl chamber diameter, inlet port depth, orifice diameter, orifice length and length of swirl chamber. Larger orifice diameter will increase the spray cone angle and lower discharge coefficient (Chu, Chou, Lin and Liann, 2008; Maniarasan and Nicholas, 2006; Yule and Widger, 1996). Shorter orifice will also increase the discharge coefficient (Yule and Widger, 1996). The effect of swirl chamber diameter is contradicted with the orifice diameter where an increase in swirl chamber diameter decreases the spray cone angle (Yule and Widger, 1996). Furthermore, Maniarasan and Nicholas (2006) had found that a reduction in swirl chamber diameter increase the liquid film thickness. Other research concludes that an increase in swirl chamber convergence angle increases the discharge coefficient and decreases the spray cone angle (Xue *et al.*, 2004).

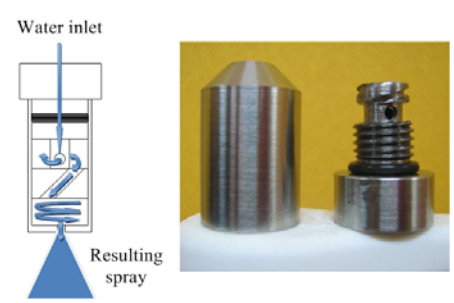



**Figure 1** Liquid flow in simplex nozzle

Other than the geometry of the nozzle, the working condition such as injection pressure and flow rate can also influence the resulting spray characteristics. Laryea and No (2003) have studied the relationship between applied voltage and injection pressure on liquid breakup length and spray angle of charge-injected electrostatic pressure swirl nozzle. They reported that an increase in applied voltage and injection pressure increases the value of spray cone angle. In recent experimental investigation done by Hussein and Atan (2008) on the breakup length and spray cone angle concluded that higher injection pressure leads to wider spray cone angle. However, at higher injection pressure, the injectors experience slight decreases in spray cone angle as the liquid film at the injector outlet contracted. Earlier numerical investigation done by Datta and Som (2000) have found that with the increase in the liquid flow rate at its lower range there occurs a sharp increase in spray cone angle but it become independent at the high range of flow rate ($Q > 1 \times 10^5$ $m^3$ $s^{-1}$). This result is in agreement with the work of Halder, Dash and Som (2003). They observed that the spray cone angle remain almost constant with the Reynolds number of the flow at inlet to the injector.

To summarize, the understanding of swirl spray characterisics is of importance since they had been used in many applications. One of the application is fuel atomization for combustion process. Yu, Li, Zhao, Yue, Chang and Sung (2005) stated that quick vaporization prior to the mixing and combustion is crucial when using liquid hydrocarbons. Swirl component is introduced in the combustion chamber to enhance fuel atomization and mixing and thus improve overall combustion efficiency. Simplex nozzles are also not so sensitive to manufacturing errors such as deviations from the prescribed diameter and surface misalignment which makes their production cheaper.

## 3.0 EXPERIMENTATION

The experimental set-up comprises of water tanks, compressed air tank, a feed line fitted with flow control valve and a pressure gauge fitted to meter the inlet flow pressure. Figure 2 shows overall experimental setup.

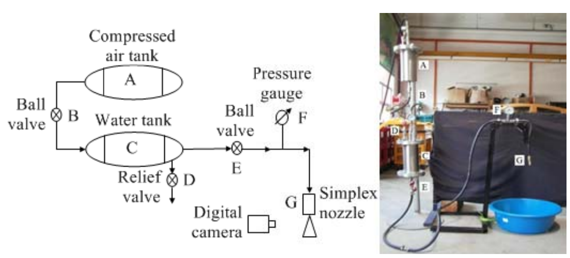



**Figure 2** Experimental setup

Both hollow-cone and solid-cone spray nozzles consist of two helicoidal slots (annular swirler) with a width of a = 1 mm. The solid-cone spray nozzles have an additional central port with a diameter of $D_c$ = 1 mm. Table 1 summarizes specifications of tested nozzles and Figure 3 explains the geometrical parameters. The spray characteristics that will be measured are discharge coefficient, spray cone angle and spray breakup length at different injection pressure.

All nozzles were tested using water to define the discharge coefficient and spray pattern characteristics. These simplex nozzles produced hollow cone shape spray; a spray in which the concentration of droplets is at the outer edge of the spray with little or no droplet in the center of the spray.

**Table 1** Specification of tested nozzles

| Nozzle | $D_s$ (mm) | $L_s$ (mm) | a (mm) | β (°) | $D_o$ (mm) | $L_o$ (mm) | $D_c$ (mm) |
|---|---|---|---|---|---|---|---|
| 1H | 11 | 1.5 | 1 | 20° | 1.5 | 1.5 | 0 |
| 2H | 11 | 1.5 | 1 | 20° | 2.0 | 1.5 | 0 |
| 3H | 11 | 1.5 | 1 | 20° | 2.5 | 1.5 | 0 |
| 4H | 11 | 1.5 | 1 | 20° | 3.0 | 1.5 | 0 |
| 1S | 11 | 1.5 | 1 | 20° | 1.5 | 1.5 | 1 |
| 2S | 11 | 1.5 | 1 | 20° | 2.0 | 1.5 | 1 |
| 3S | 11 | 1.5 | 1 | 20° | 2.5 | 1.5 | 1 |
| 4S | 11 | 1.5 | 1 | 20° | 3.0 | 1.5 | 1 |

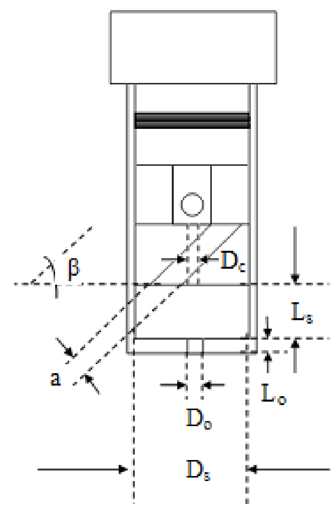



**Figure 3** Simplex nozzle geometrical parameters

The supply water pressure was measured by bourdon type pressure gauge and controlled by ball valve. The injector is mounted on a vertical plane with the injector orifice being pointed downwards. A 14 mega pixels digital camera was used to capture images of the spray. The photographs were scanned and magnified in a computer for the measurement of the spray cone angle and spray break up length. Figure 4 shows the photograph of the hollow cone spray at injection pressure of 4 bar with thin lines indicate the spray boundary and the breakup point.

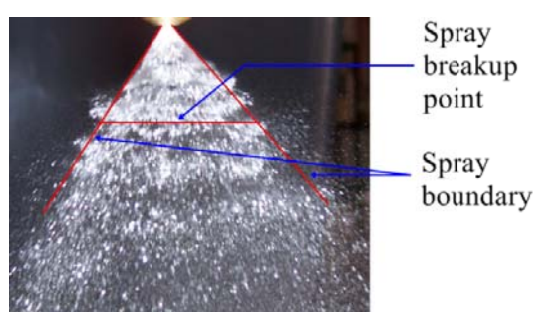



**Figure 4** Typical hollow cone spray

## 4.0 RESULT AND DISCUSSION

A total of 56 tests were performed with inlet pressure ranging from 100 – 700 kPa. The relationship between the breakup length and injection pressure is presented in Figure 5.

It was observed that all nozzles had similar trend; the breakup length decreased with an increase in injection pressure. This is due to the fact that higher injection pressure results in higher resultant axial velocity component, which increase the tendency of the liquid film to disintegrate earlier. It has also been observed that nozzle with larger orifice diameter produces longer liquid film. This observation possibly can be explained as follows; larger orifice tends to increase the spray film thickness, in which increase the resistance of spray to disintegrate earlier. The investigation also found that hollow-cone spray produced longer liquid film compared to solid-cone spray. This is because hollow-cone spray has the highest azimuthal velocity component which tends to lengthen the liquid film. The solid-cone spray has less swirl strength as a result of axial velocity component from the central port.

Figure 6 compares the discharge coefficient of simulated flow with different orifice diameter. The discharge coefficient is calculated using the relation:

$$C_d = \frac{\dot{m}}{A\sqrt{2\rho\Delta P}} \quad (1)$$

where, ρ is the density of water and *A* is the orifice area.

Reynolds number is calculated using relation given by Halder *et al.*, (2003):

$$\mathrm{Re} = \frac{2\rho\dot{V}}{\mu\pi R_1} \quad (2)$$

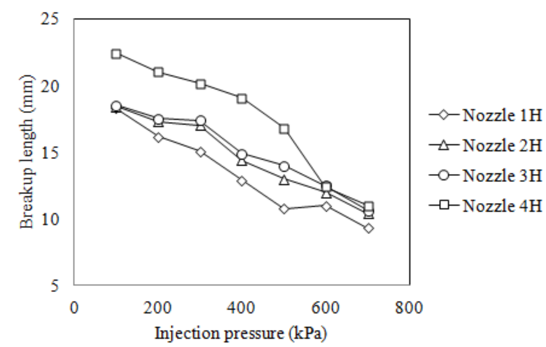
where ρ and μ are water density and viscosity respectively and $R_1$ is swirl chamber radius.

Nozzles 3S, 4H and 4S shows an approximate direct proportion between Reynolds number and discharge coefficient for Reynolds number above 4000. However, discharge coefficient of other nozzles remains almost constant with only little fluctuation within the tested range of inlet flow's Reynolds number. It can be said that the discharge coefficient is almost uninfluenced by the injection pressure for all nozzles. This is because high Reynolds number implies an increase in the flow through the annular swirler which gives rise to the counter weighing effects of increased strength of swirl and its subsequent decay due to friction in the injector, which in turn results in almost constant values of discharge coefficient with respect to Reynolds number.

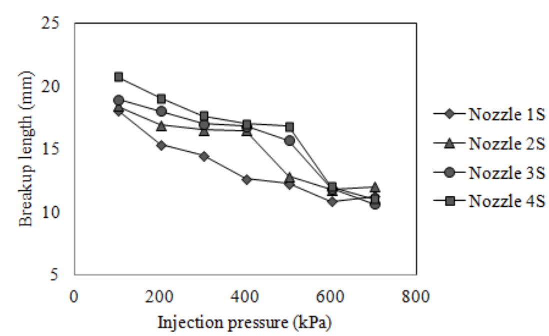
It has been observed for both hollow-cone and solid-cone spray nozzles that the nozzle with largest orifice diameter has the lowest discharge coefficient, which confirms previous observation by Chu, Chou, Lin and Liann (2008), Maniarasan and Nicholas (2006) and Yule and Widger (1996). This is because larger orifice diameter increases the swirling motion inside the swirl chamber and hence the air core which finally results in low discharge coefficient.

Spray cone angle is another studied parameter and the effect on injection pressure is shown in Figure 7. It can be concluded that the increase in injection pressure increased the spray angle, irrespective of the shape of the sprays. The major reason is that the angular velocity increases with pressure difference which tends to widen the liquid film at the nozzle outlet. However, nozzles 2H, 3H, 3S and 4S experience slight decreases in spray angle as the injection pressure reach 6 bar. The explanation to this observation is that higher pressure leads to lower radial velocity component, and hence the resulting liquid film at the injector outlet contracted. It is also found that nozzle with largest orifice produces widest spray. This observation is in agreement with previous research done by Maniarasan *et al.* (2006).

Figure 7 also shows that hollow-cone spray nozzles produce wider spray cone angle compared to solid-cone spray nozzles. This trend of variation can be attributed to the fact that the stream from the central port for solid-cone spray nozzles increase the resistance offered by the injector to the swirling motion inside it and finally results in lower value of spray cone angle. The same argument may be used to explain why hollow-cone spray nozzles produce highest spray angle. The liquid enters the swirl chamber only through helicoidal slots, hence the axial velocity component is only from one source (instead of two sources for solid-cone spray nozzles) which tends to widen the liquid film at the nozzle outlet.

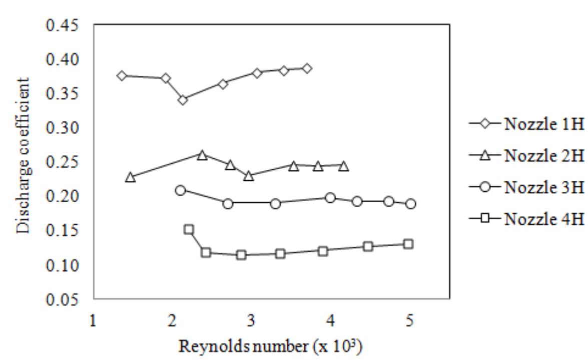



(a)

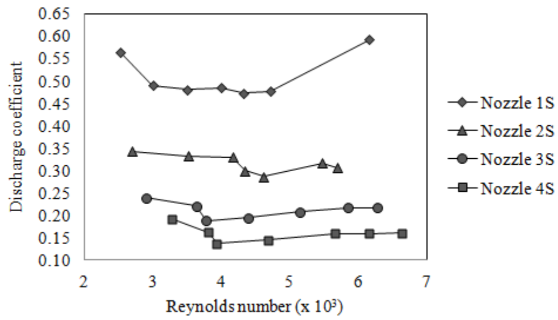



(b)

**Figure 5** Effects of injection pressure on breakup length, (a) hollow-cone spray nozzles and (b) solid-cone spray nozzles

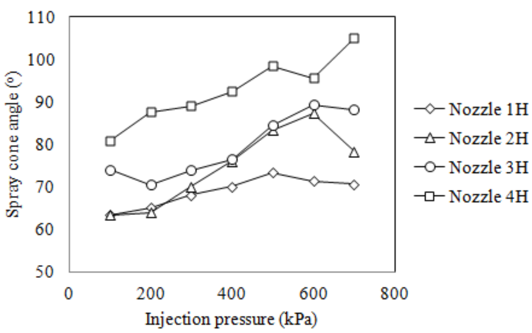



(a)

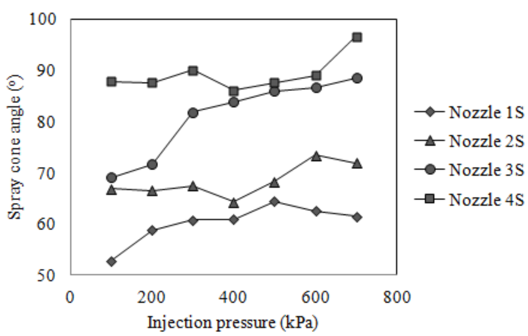



(b)

**Figure 6** Effects of inlet Reynolds number on discharge coefficient, (a) hollow-cone spray nozzles and (b) solid-cone spray nozzles




(a)




(b)

**Figure 7** Effects of injection pressure on spray angle, (a) hollow-cone spray nozzles and (b) solid-cone spray nozzles

## 5.0 CONCLUSION

Experimental work was conducted to evaluate the characteristics of swirl spray that emanates from nozzles with different orifice diameter. Those characteristics were based upon calculated values of breakup length, discharge coefficient and spray cone angle and as a function of injection pressure and Reynolds number. In summary, the conclusions are listed as below.

(1) The spray cone angle and breakup length is affected by the injection pressure. Higher injection pressure leads to shorter breakup length and wider spray angle
(2) Nozzle with largest orifice diameter produces longest breakup length and widest spray cone angle.
(3) Discharge coefficient of tested nozzles is almost uninfluenced by the inlet flow's Reynolds number. The nozzle with largest orifice diameter has the lowest discharge coefficient.
(4) Hollow-cone spray nozzles produced longer liquid film and wider spray cone angle compared to solid-cone spray nozzles.

## Acknowledgement

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