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Effects of flow and atomizer parameters on the spray cone angle in a hollow cone swirl atomizer

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ABSTRACT
The experimental and numerical studies have been carried out to determine the influences of nozzle flow and nozzle geometry on the spray cone angle in a hollow cone swirl atomizer. The numerical study is based on the solution of conservation equations for mass and momentum and k-ε model is adopted for turbulent quantities. Experiments have been carried out with a number of nozzles fabricated by perspex material. The spray cone angle has been measured from the photographs of spray at outside the nozzle taken by a camera. From both numerical and experimental studies the value of spray cone angle ψ from an atomizer is found to increase sharply with an increase in inlet Reynolds number Re at its lower range but become almost constant with Re at its higher range. The spray cone angle ψ increases with an increase in the value of D_o/D_s or α and it decreases with an increase in the value of D_p/D_s or L_o/D_s.

Keywords: Spray cone angle, Swirl chamber, Simplex nozzle, Air core diameter

1. Introduction

The basic purpose of a pressure swirl atomizer is to produce a widely dispersed spray of atomized liquid. The function of the atomizer is not only to disintegrate the liquid into small drops but also to discharge these drops into the surrounding gaseous medium in the form of a symmetric, uniform spray. The Spray is of two types such as “solid cone” and “hollow cone” spray. A solid cone spray is produced with plain orifice atomizers and certain types of pressure swirl atomizers, where the drops are fairly evenly dispersed throughout the entire spray volume. For many combustion applications, a solid spray is considered undesirable because it can give rise excessive concentrations of soot and particulates in the exhaust gases. In such situations a hollow cone spray of wide cone angle is generally preferred, where the larger drops are concentrated in the periphery and there is no liquid drop in the central region of the spray. Hollow cone, pressure swirl atomizers are widely used as fuel injectors in gas turbine and in rocket engine. The hollow conical structure of the spray incurs appreciable exposure to influence the surrounding ambiance. Generally, an increase in spray cone angle increases the extent of this exposure leading to improved atomization, better fuel-air mixing, and better dispersion of the fuel drops throughout the combustion volume. The cone angle is important because it influences the axial and radial distributions of the fuel droplets and ultimately the efficiency and emissions. Experience with gas turbine combustors has shown that swirl atomizer with wide spray cone angle are usually characterized by a good “pattern factor,” i.e. a fairly uniform distribution of temperature in the combustion products flowing into the turbine, and by relatively low concentration of soot in the exhaust gases. Irregularities in circumferential distribution of fuel can also adversely affect the liner wall temperature and turbine blade life. For these reasons, considerable interest exists in the manner and content to which spray cone angle is influenced by atomizer design features, liquid properties and nozzle flow.

In a hollow cone spray atomizer, liquid at high pressure is supplied to the atomizer through tangential entry ports and is finally discharged through an outlet orifice in the form of a hollow cone spray. The geometry of such nozzle is usually a converging passage followed by a short cylindrical orifice is shown in Fig.1.

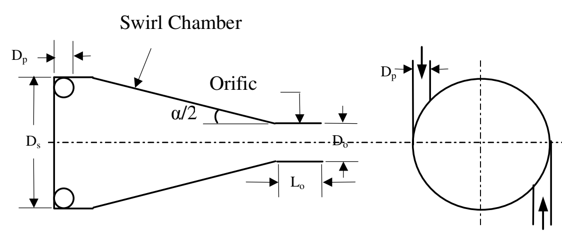

Fig.1 A Typical Hollow Cone Type Conical Swirl Atomizer

The most important picture of the flow in such a nozzle is the formation of a central air core due to purely tangential entry of the liquid. Liquid is discharged from the nozzle in the form of a thin hollow conical sheet due to the formation of a central air core in swirl nozzle, which breaks up and produces a hollow cone atomized spray. The thickness of the liquid sheet coming out of the nozzle and the effective flow area of the nozzle depends on the size of the air core. Therefore, the air core within the atomizer has a direct influence on the important performance parameters of the atomizer, namely, the degree of atomization (mean drop diameter of the atomized spray), the coefficient of discharge, and the spray cone angle.

According to Taylor’s [1] inviscid theory, the spray cone angle is determined solely by the swirl chamber geometry and is a unique function of a single

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dimensionless geometrical parameter of the nozzle defined as nozzle constant ($K = A_p/D_sD_o$), where, A_p is the area of the tangential entry port and D_s, D_o are the diameters of swirl chamber and orifice respectively. This relationship is modified in practice with viscous effects later. Giffen and Muraczew's [2] analysis of the nonviscous liquid flow in a swirl atomizer, also expressed the spray cone angle as a function of nozzle dimensions only. It led to the following expression for the mean value of the spray cone half angle.

$$\sin\theta_m = \frac{(\pi/2)(1-X)^{1.5}}{K\left(1+\sqrt{X}\right)(1+X)^{0.5}} \tag{1}$$

where, $K = A_p/D_sD_o$ and $X = A_a/A_o$ of which A_a is the area of cross section of air core.

To eliminate one of these variables, Giffen and Muraczew [2] also derived the following expression for K in terms of X

$$K = \frac{\pi(1-X)^{1.5}}{\sqrt{32}\ X} \tag{2}$$

Eq.(1) and (2) allow the spray cone angle to be expressed in terms of either X or K. Rizk and Lefebvre [3] also derived the equation for the spray cone angle in terms of X as

$$\cos^2\theta_{max} = \frac{1-X}{1+X} \tag{3}$$

Where, θ_{max} is spray cone angle measured at the outer boundary and X is directly related to the liquid film thickness 't' at the final discharge orifice as,

$$X = \frac{(D_o - 2t)^2}{D^2_o} \tag{4}$$

According to Eq. (1) and (3), the spray cone angle is a function of atomizer dimension only and is independent of liquid properties, ambient air properties, and injection pressure. But Rizk and Lefebvre [4] and some other researchers reported that the density, viscosity of liquid, injection pressure, and atomizer dimensions as well have the effect on film thickness and thereby the spray cone angle.

A host of articles in the field of hollow cone swirl nozzle is available in literature. The developments in the field of swirl nozzle were mainly due to Rizk and Lefebvre [3,4], Kutty et al. [5], Som and Mukherjee [6,7], Som [8], Halder et al.[9,10] Suyari and Lefebvre [11], Yule et al. [12], Jeng et al. [13], Liao et al. [14], Sakman et al. [15] and Datta and Som [16]. All those works brought about an understanding of the swirling flow inside a hollow cone spray nozzle and attempted in evaluating the liquid film thickness or air core diameter at the discharge orifice, the flow number and the spray cone angle either from empirical studies or from theoretical analyses.

The main difficulty in the numerical simulation of flow in a hollow cone swirl atomizer is the accurate tracking of the interface between the two phases. Several solution methods for the free surface flow are available in the literature. Some of them are unable to give exact location of the interface and some of them are computationally expensive. In the recent era, Jeng et al. [13], Liao et al. [14] and Sakman et al. [15] used a computational model based on Arbitrary Lagrangian-Eulerian (ALE) method for the simulation of flow in a hollow cone swirl nozzle. Halder et al. [10] and Jeng et al. [13] reported the bulging shape of an air core at entrance to the orifice in a hollow cone swirl nozzle. Halder et al.[10, Liao et al. [14], Sakman et al. [15] and Datta and Som [16] investigated numerically the nozzle performance parameters like, the coefficient of discharge, the spray cone angle, and the liquid film thickness or air core diameter at orifice with the flow and nozzle dimensions. In the present paper the authors predicted the spray cone angle, from both experimental investigation and numerical solution of two phase turbulent swirling flow in the atomizer following the minimum resistance principle proposed by Datta and Som [16] in predicting the air core with a uniform diameter in a hollow cone type conical swirl atomizer.

2. **Model Details**

The theoretical analysis refers to a typical simplex atomizer as shown in Fig.1. Conservation equations for axisymmetric flow of liquid (water) in the annular region and air in the central region through the nozzle were solved simultaneously satisfying the respective boundary conditions by an explicit finite difference computing technique developed by Hirt and Cook [17] following the original MAC(Marker and Cell) method due to Harlow and Welch [18]. The steady state solution of flow was achieved by advancing the equations in time till the temporal derivatives of all the variables fall below a pre-assigned small quantity ∂. The standard k-ε model has been adopted for the computation of turbulent flow of liquid and a laminar flow modeling is adopted for flow of air in the atomizer. The space derivatives of the diffusion terms were discretized by the central differencing scheme while the advection terms were discretized by the hybrid differencing scheme based on the local Peclet number Pe associated with the cell. A 66X36 variable sized adaptive grid system was considered with clustered cells near the inlet and wall. The variations in the size of grids were made uniformly. It was checked by further refinement of the cells (with doubling and quadrupling the number of grids in both the directions) and found not to change the velocity (axial and tangential) components and turbulent kinetic energy by more than 2%.

2.1 Spray cone angle

The spray cone angle was calculated from the following formula

$$\psi = 2\cos^{-1}\left(\frac{\bar{v}_{zo}}{\left(\bar{v}_{zo}^2 + \bar{v}_{ro}^2 + \bar{v}_{\theta o}^2\right)^{\frac{1}{2}}}\right) \tag{5}$$

where, the dimensionless average axial, radial, and tangential components of liquid velocities at the atomizer exit were determined as

$$\bar{v}_{zo} = \frac{1}{\left(\frac{R_o}{R_1}\right)^2} \tag{5a}$$

$$\bar{v}_{ro} = \frac{\int_0^{R_o} r\, v_z v_r\, dr}{\int_0^{R_o} r\, v_z\, dr} \tag{5b}$$

$$\bar{v}_{\theta o} = \frac{\int_0^{R_o} r\, v_z\, v_\theta\, dr}{\int_0^{R_o} r\, v_z\, dr} \tag{5c}$$

3. Experimental Investigation

3.1 Fabrication of Nozzles

A number of swirl nozzles of the geometrical shape as shown in Fig. 1 with different geometrical dimensions were fabricated with transparent perspex material. The different geometrical dimensions of the nozzles fabricated are given below:

D_o: 2, 3 & 4 mm, D_p: 2.5, 3.75 & 5 mm, D_s: 8 mm, L_o: 2, 4 &12 mm and α: 20°, 40° & 60°

The dimensions of the nozzles are in conformity to the available literature and to the values usually employed in the design of nozzles in practice.

3.2 Experimental Set up

A line diagram of the test rig is shown in Fig.2. A multistage centrifugal pump (P) was used to supply water at a high pressure through two symmetrical tangential ports to the nozzle (N). The flow to the nozzle was controlled by the valves (V_1 and V_2) and was measured by a rotameter (R). The injection pressure to the nozzle was also recorded by a bourdon type pressure gauge (G) which was calibrated with a dead weight tester before the experiment. The rotameter was calibrated against the direct method of flow measurement by collecting water in a volumetric tank during a known interval of time.

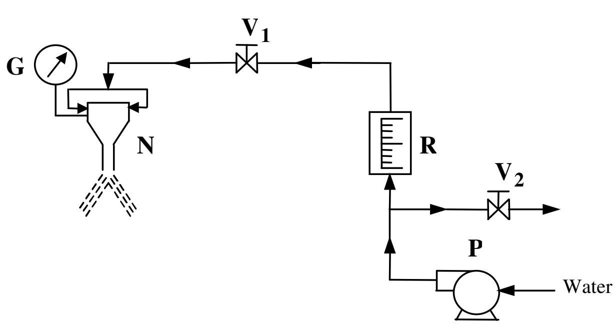

Fig.2 Line Diagram of the Experimental Set up

The spray cone from the nozzles were photographed by a wide angled lens camera with flood light illumination. A photograph of a typical spray cone is shown in Fig. 3. The photographs were scanned and the spray cone angles were measured from a magnified picture in a computer. The uncertainty in the measured values of spray cone angle was found to be ± 3.19% with a confidence limit of 95%. This was determined from an almost fixed measurement error (Bias error) of ± 2.1% due to a large magnification of spray cone compared to the resolution in the linear scale of measurement, and a precision error of ± 2.4% with 95% confidence limit. The precision error was found out from a large population of data generated at each and every set of operating conditions.

$D_o/D_s = 0.25$, $D_p/D_s = 0.315$, $Lo/D_s = 0.5$, $\alpha = 40°$, $Re = 1.65 \times 10^4$

Fig.3 The Spray Cone from a Hollow Cone Swirl Nozzle

4. Results and Discussion

The computed velocity field in an atomizer is shown in Fig.4. A small re-circulating zone at the near wall region is observed in the flow of liquid phase at the upstream section of the nozzle. A big central recirculation zone is also observed almost throughout the nozzle. The central recirculation zone appears to be confined within the air core in the flow through the nozzle.

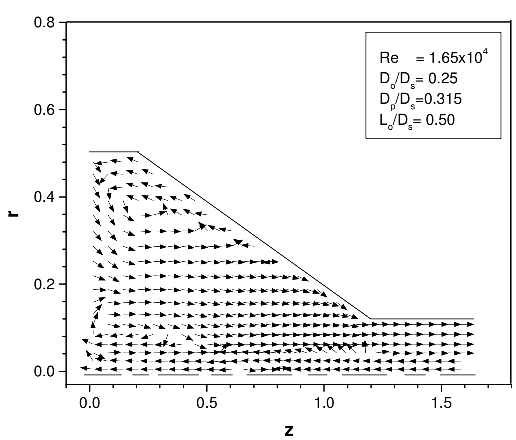

Fig.4 A Velocity Field within the Nozzle

4.1 Effects of Inlet Reynolds Number on Spray Cone Angle in a Hollow Cone Swirl Atomizer

It is found from Fig. 5 that for a hollow cone swirl atomizer, the spray cone angle of the spray from the nozzle increases with an increase in the Reynolds number Re at inlet to the nozzle at its lower range but becomes almost independent of Re at its higher range. Both the numerical and experimental results show the similar trends along with a fair agreement but the experimental values are always less than the numerical values with a maximum deviation of 9.3%. An increase in the inlet Reynolds number Re for a nozzle of given geometry is always accompanied by an increase in the tangential velocity of injection to the nozzle. This causes the counterweighing effects by increasing both the swirling strength at inlet and its subsequent decay due to frictional effect in the nozzle. In the lower range of Re, the increase of swirl predominates the adverse effect of frictional resistance, while in the higher range of Re, the two effects counter balance each other resulting in an almost constant value of spray cone angle. The trend of variation of spray cone angle with inlet Reynolds number Re is similar, as depicted in Fig. 5, for all conical nozzles with different geometrical dimensions.

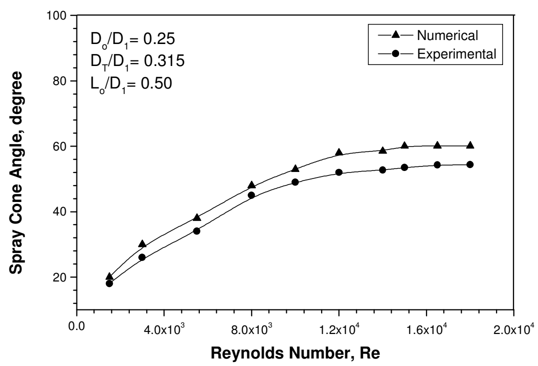

Fig. 5 Effect of Reynolds Number on Spray Cone Angle

4.2 Effects of Atomizer Dimensions on Spray Cone Angle in a Hollow Cone Swirl Atomizer

Table 1 shows the influences of various dimensionless geometrical parameters on the spray cone angle. It is observed that the spray cone angle increases with an increase in the value of the ratio of orifice diameter to swirl chamber diameter D_o/D_s or swirl chamber cone angle α and with a decrease in the ratio of the diameter of tangential entry port to that of swirl chamber D_p/D_s or the ratio of the orifice length to swirl chamber diameter L_o/D_s. Amongst the dimensionless geometrical parameters of the nozzle, the ratio of orifice diameter to swirl chamber diameter D_o/D_s and the ratio of tangential entry port diameter to swirl chamber diameter D_p/D_s have the profound influence on spray cone angle. The numerically predicted and experimentally observed values are in well agreement with each other and show a deviation of 3.1% to 9.3% in the entire range of the investigations.

The trends of variations of spray cone angle with the geometrical dimensions of the atomizer can be explained as the increase in either orifice diameter D_o or swirl chamber cone angle α and the decrease in length of orifice L_o in fact reduces the resistance offered by the nozzle to the swirling motion of liquid inside it, while a decrease in inlet tangential port diameter D_p for a given flow rate, increases the strength of swirling motion by increasing the tangential velocity of injection to the nozzle.

Table 1 Influence of Nozzle Dimensions on Spray Cone Angle in a Simplex Nozzle

a. Influence of D_0/D_s (D_p/D_s = 0.315, L_o/D_s = 0.5, α = 40^o)

D_o/D_s	*Spray Cone Angle, ψ degree*	
	Numerical	Experimental
0.25	60.12	54.5
0.375	63.78	58.8
0.5	66.64	63.1

b. Influence of D_p/D_s (D_o/D_s = 0.25, L_o/D_s = 0.5, α = 40^o)

D_p/D_s	*Spray Cone Angle, ψ degree*	
	Numerical	Experimental
0.315	60.12	54.5
0.468	52.58	48.6
0.625	35.29	32.8

c. Influence of L_o/D_s (D_p/D_s = 0.315, D_o/D_s = 0.25, α = 40^o)

L_o/D_s	Spray Cone Angle, ψ degree	
	Numerical	Experimental
0.25	62.12	58.28
0.5	60.12	54.5
1.5	53.62	50.4

d. Influence of α (D_p/D_s = 0.315, D_o/D_s = 0.25, L_o/D_s = 0.5)

Swirl Chamber Cone angle α	Spray Cone Angle, ψ degree	
	Numerical	Experimental
20^o	55.1	50.3
40^o	60.12	54.5
60^o	65.52	63.5

5. Conclusions

- The values of spray cone angle increase sharply with an increase in inlet Reynolds number Re at its lower range but become almost independent of Re at its higher range
- The spray cone angle increases with an increase in the values of D_o/D_s or α and with a decrease in the values of D_p/D_s or L_o/D_s.
- Numerical results of spray cone angle show a fair agreement with the experimental results with a maximum deviation of 9.3%.

NOMENCLATURE

A_p : area of tangential entry ports
D_o : diameter of orifice of a conical nozzle
D_p : diameter of tangential entry port
D_s : diameter of swirl chamber of a conical nozzle
L_o : length of orifice of a conical nozzle
Q : total flow rate through the nozzle
r : radial distance
Re : Reynolds number at inlet to the nozzle
R_o : radius of the orifice
v_z : velocity component in axial direction
v_r : velocity component in radial direction
v_θ : velocity component in circumferential direction
z : axial distance

Greek Letters

α : swirl chamber cone angle
μ : viscosity
ρ : density
ψ : spray cone angle

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