DESIGN AND EXPERIMENTAL INVESTIGATION OF 60^O PRESSURE SWIRL NOZZLE FOR PENETRATION LENGTH AND CONE ANGLE AT DIFFERENT PRESSURE

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ABSTRACT

The spray penetration is of prime importance for combustion chamber design. Over penetration of the spray leads to impingement of the fuel on the combustion chamber wall and if the walls are cold it causes the fuel wastage. Optimum engine performance is obtained when the spray penetration is matched to the size and geometry of the combustion chamber and methods for calculating penetration. The present work describes the design of pressure swirl nozzle for half spray cone angle of 30° and outline detail of experimental setup, to investigate effect of pressure on penetration length and spray cone angle. Designed pressure swirl nozzle experimentally investigated at different pressures ranging from 3bar to 18 bars in the step of 3 bars. In gas turbine combustor, spray angle has strong influence on ignition performance, flame blowout limits and pollutants, emissions of unburned hydrocarbons and smoke. The results for penetration length and spray cone angle suggest that at designed pressure, pressure swirl nozzle gives best performance.

KEYWORDS: *A*nnular Combustor, Penetration Length, Pressure Swirl Nozzle, Spray Cone Angle.

I. INTRODUCTION

The transformation of bulk liquid into spray and other physical dispersions of small particles in a gaseous atmosphere are of importance in several industrial processes and have many other applications in agricultural, metrology and medicine. A number of spray devices have been developed for this purpose, and they are generally designated as atomizers or nozzles [1]. Among these, pressure-swirl atomizers or simplex atomizers are commonly used for liquid atomization due to their simple design, ease of manufacture, and good atomization characteristics. The process of atomization is one in which a liquid jet or sheet is disintegrated by the kinetic energy of the liquid itself or by exposure to high velocity air or gas, or as a result of mechanical energy applied externally through a rotating or vibrating device.

Combustion of liquid fuels in diesel engines, spark ignition engines, gas turbine engines, rocket engines and industrial furnaces is dependent on effective atomization to increase the specific surface area of the fuel and thereby achieve high rate of mixing and evaporation. In most combustion systems, reduction in mean drop size leads to higher volumetric heat release rate, easier light up, a wider burning range and lower exhaust concentrations of pollutant emissions.

Phase Doppler anemometry (PDA) is widely used for the measurement of drop size and velocity in sprays [2, 3, 4]. PDA combines the measurement of scattered light intensity with laser Doppler anemometry (LDA) to obtain simultaneous droplet size and velocity measurements. PDA is most favorable for measurement of spray evolution. The breakup of liquid sheets and the dense spray region is normally not considered here.

PDA is a point measurement technique and cannot be used to obtain instantaneous spatial information on velocity, droplet size and concentration. With a relatively new imaging technique, called interferometric particle imaging (IPI), these instantaneous spatial information can be obtained. IPI has been developed into a commercial product by Dantec Dynamics. It is a technique for determining the diameter of transparent and spherical particles in a whole field from out-of-focus particle images. The velocity of each particle is simultaneously determined using particle tracking velocimetry (PTV) on focused images. The IPI/PTV technique is tested on hollow-cone water sprays produced by pressure-swirl atomizers in [5] and [6]. The main limitation of the technique is that it cannot be used at high droplet concentrations.

When a liquid is discharged through a small aperture under high applied pressure, the pressure energy is converted into kinetic energy. A simple circular orifice is used to inject a round jet of liquid into the surrounding air. That is known as plain orifice type atomizer. Combustion applications for plain orifice atomizers include turbojet, afterburner, ramjet, diesel engines and rocket engines.

Pressure swirl (simplex) atomizer is shown in Figure1. A circular outlet orifice is preceded by a swirl chamber into which liquid flow through a number of tangential holes or slots. The swirling liquid creates a core of air or gases which extents from the discharge orifice to the rear of the swirl chamber. The liquid emerges from the discharge orifice as an annular sheet, which spreads radially outward to form a hollow conical spray. Included spray angle ranges from 30^o to almost 180^o, depending on the application. Atomization occurs at high delivery pressures and wide spray angles. For some applications a spray in the form of the solid cone is preferred. This can be achieved by using an axial jet or some other device to inject drops into centre of the hollow conical sheet.

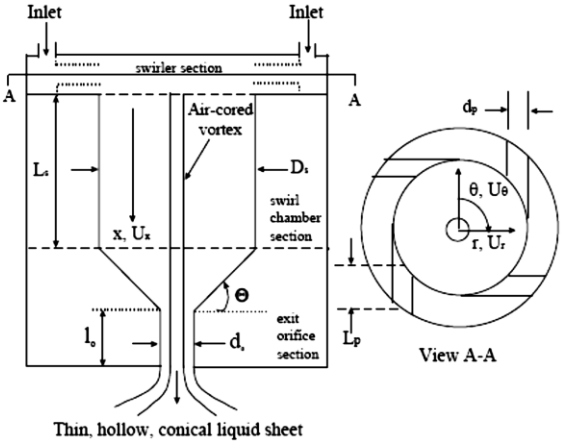

Figure 1. Schematic of Simplex Atomizer Geometry [7]

Square spray is a solid cone nozzle, but the outlet orifice is specially shaped to the spray into a pattern that is roughly in the form of square. Atomization quality is not as high as conventional hollow cone nozzle.

A drawback of all type of pressure nozzle is that the liquid flow rate is proportional to the square root of the injection pressure differential. In practice, this limits the flow range of simplex nozzle about 10:1. The duplex nozzle overcomes this limitation by feeding the swirl chamber through two sets of distributor slots.

Dual orifice is similar to the duplex nozzle except that two separate swirl chambers are provided. Two swirl chambers are housed concentrically within a single nozzle body to form a nozzle within a nozzle. The Spill return is a simplex nozzle but with a return flow line at rear or side of the swirl chamber and a valve to control the quantity of liquid removed from the swirl and returned to the supply.

The present paper discusses the design and experimental investigations on designed pressure swirl atomizer of annular type combustion chamber for small gas turbine application.

II. DESIGN METHOD [8]

The aim of the design is to determine the dimensions of a simplex swirl atomizer for the following data: Q or G, α, ΔP, ρ and υ. First one calculates the basic dimensions incorporated in geometric constant K and then the other dimensions.

The first phase of calculations refers to an ideal liquid. For given angle α from Figure 2, determine geometric constant K and subsequently discharge coefficient C_D. From (1), calculate the discharge orifice diameter.

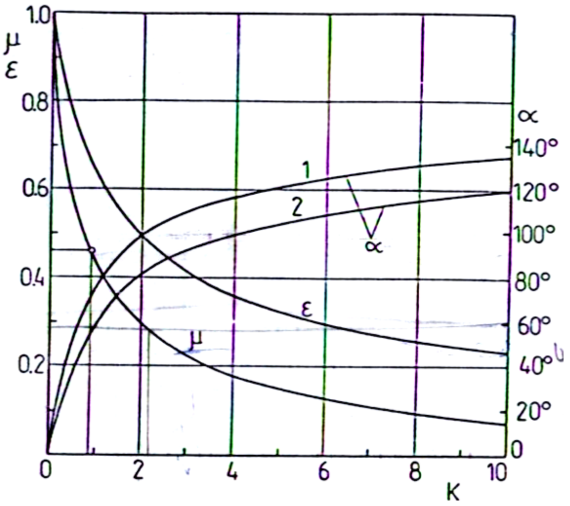

Figure 2. Dependence of the Discharge Coefficient C_D; Inlet Orifice Filling Efficiency ε and Spray Angle α on Geometric Constant of Swirl Atomizer k [8]

$$G = \rho\, Q = C_D A_0 \sqrt{2\rho \Delta P} \tag{1}$$

$$d_0 = \sqrt{\frac{4G}{\pi\, C_D\, \sqrt{2\rho P_t}}} \tag{2}$$

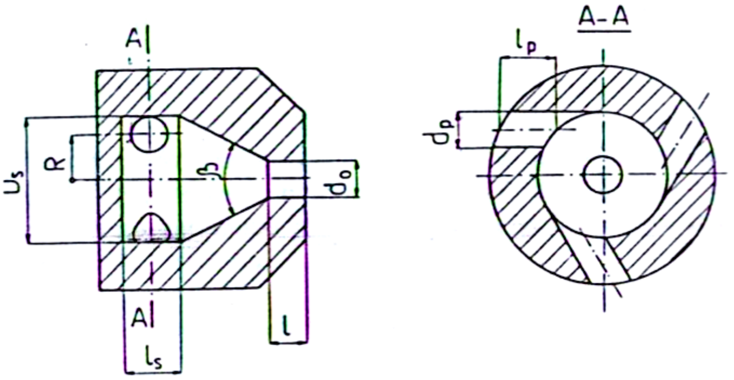

Figure 3. Basic dimensions of a Simplex Swirl Atomizer [8]

The geometric constant contains three unknown quantities, R, i, d_p

$$K = \frac{2\, R\, d_0}{i\, d_p^2} \tag{3}$$

From the unknown quantities listed above, two of which have to be assumed. It is most convenient to assume the number of orifices and radius of swirl chamber. Most commonly, i = 2 to 4 and R = (2 to 5) r_0 are used. From (3), calculate the diameter of tangential inlet orifice.

$$d_p = \sqrt{\frac{2\, R\, d_0}{i\, K}} \tag{4}$$

In the case of orifice with a shape other than circular, instated of d_p, determine A_p. The second phase of calculations refers to the assessment of viscosity effect. The Reynolds number at the inlet to the atomizer is

$$Re = \frac{v_p\, d}{\vartheta} \tag{5}$$

Where, d is the equivalent diameter of the orifice

$$\frac{\pi\, d^2}{4} = i\, \frac{\pi\, d_p^2}{4} \quad \text{and} \quad v_p = \frac{4G}{\rho\, i\, \pi\, d_p^2}$$

So (5), can be reformed as

$$Re = \frac{4G}{\pi\, \rho\, \vartheta\, \sqrt{i} d_p} \tag{6}$$

Friction coefficient λ follows from the formula

$$\log \lambda = \frac{25.8}{(\log Re)^{2.58}} - 2 \tag{7}$$

The value of λ determined from (7) is significantly larger than would follow from the equation used in hydraulics. This is due to high transverse pressure gradient in the wall boundary.

The effect of liquid viscosity can be neglected when the following inequality is satisfied:

$$\frac{B^2}{i} - K \leq \frac{2}{\lambda}(\Phi^{1.5} - 1) \tag{8}$$

where Φ = ratio of discharge coefficient C_D for a viscous and an ideal liquid.

Considering the selection of the value of radius R, remember that R should be small and simultaneously the area of the inlet orifice should be small in order to overcome the viscosity barrier. The higher K means larger value of α is required; the radius R should be smaller. Also, the smaller the flow rate and the higher the liquid viscosity, the smaller radius R should be. For liquids with moderate viscosity we should assume

$$B = \frac{R}{r_p} < 4 - 5$$

which follows from the fact that the following condition should be satisfied:

$$\frac{B^2}{i} - K < 5 - 10$$

If we assume value of B and R very small, the overall atomizer dimensions become too small.

In tangential inlet orifice, liquid contraction occurs and therefore the actual area of cross section A’ of each inlet orifice should be increased in such a way that jet has cross section area A_p. From the definition of the contraction coefficient

$$\varphi = \frac{A_p}{A_p'} = \left(\frac{d_p}{d_p'}\right)^2 \quad \text{hence} \quad d_p' = \frac{d_p}{\sqrt{\varphi}} \tag{9}$$

The contraction coefficient is assumed to be φ = 0.85 -0.90[8].

The third phase of the calculation concerns the determination of the remaining dimensions of the atomizer.

The diameter of the swirl chamber D_s is

$$D_s = 2\,R + d_p'$$

The length of the swirl chamber l_s should be slightly larger than that of the inlet orifice. It suffices for a liquid to make one fourth to one third of rotations, since a long chamber determines the atomization condition. The inlet orifice should have the proper length l_s so that jets entering the swirl chamber are not deflected from the tangential direction. The length of the swirl chamber is taken as (1.5 to 3)d'_p [8].

The discharge orifice should not be too long in order not to decrease angle α. For $K_\lambda < 4 – 5$, l = (0.5 to1.0) d_0 [8] is recommended and for $K_\lambda > 4 - 5$, l = (0.25 to 0.5) d_0 [8].

The calculation method presented here is also applicable to atomizers with a swirling insert. In that case the radius of swirling R is equal to the radius of swirling grooves. A_p is a cross section of an individual groove and i is the number of groove.

Here the pressure swirl atomizer is designed for kerosene having the mass flow rate of 7.199×10^{-3} kg/s, injection pressure of 18 bar and half spray cone angle of 30°. From this inlet parameters output for design of pressure swirl atomizer is summarized as in Table 1.

Table 1. Summary of design parameters for pressure swirl nozzle

Design Data	**Nozzle Half Spray Angle 30°**
Discharge Orifice Diameter, d_0	0.8 mm
Distance of Tangential Inlet Port from Central Axis, R	1.4 mm
Number of Tangential Inlet Ports, i	4
Tangential Inlet Port Diameter, d_p	0.6831 mm
Swirl Chamber Diameter, D_s	3.53 mm
Length of Swirl Chamber, l_s	7.06 mm
Length of Inlet Port, l_p	1.46 mm
Length of Discharge Orifice, l	0.56 mm

Figure 4. Photographic View of Designed Nozzle

III. EXPERIMENTAL INVESTIGATION

The experimental setup is developed for the measurement of spray characteristics like penetration length and spray cone angle at different pressure varying from 3 bars to 18 bars with the increment of 3 bars. Figure 5 shows the schematic diagram of the experimental setup.

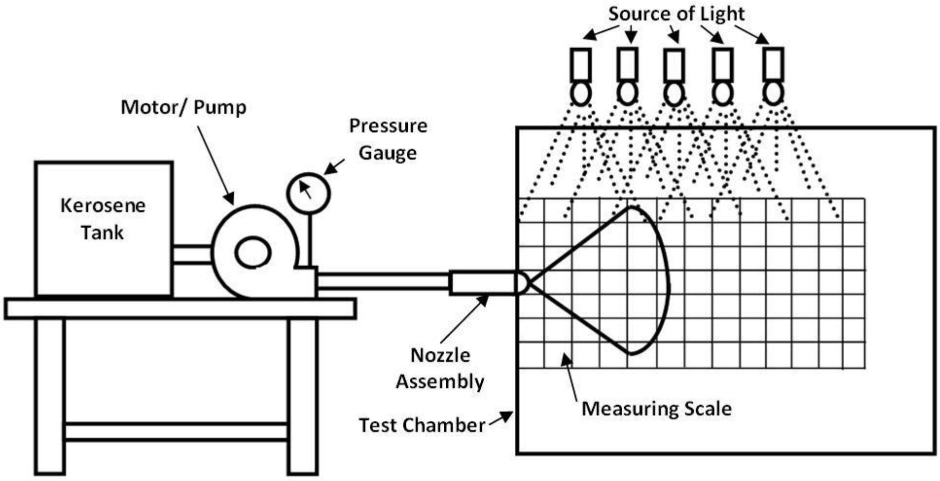

Figure 5. Schematic Diagram of Experimental Setup

Based on maximum flame diameter and flame length [9], the test chamber dimensions for mass flow rate of 7.199×10^{-3} kg/s of kerosene (for the selected nozzle) are selected as 2m x 1m x 1m. The test chamber is having three sides of M. S. plate, having thickness of 3 mm. The other three sides are of acrylic sheets, thickness of 10 mm. The acrylic sheet is used for viewing the spray. During the experimentation in daylight it is not possible to get clear visualization of the spray cone angle and the penetration length so experiments are conducted under blue lighting conditions. Photography carried out by high speed camera to evaluate spray cone angle and penetration length at different injection pressure. Figure 6 shows the test chamber.

Figure 6. Test Chamber

IV. RESULTS AND DISCUSSION

The experimental setup for the measurement of spray penetration length and cone angle is shown in the Figure 6. The Kerosene is sprayed in the test chamber from designed pressure swirl nozzle having half spray angle of 30° at pressure of 3 bar, 6 bar, 9, bar, 12 bar,15 bar and 18 bar. The penetration length and cone angle are measured using high speed camera (Nikon D 60). For the easy of measurement, the grids of illuminated strips of size 5cm × 5cm are attached on the acrylic sheet. Figure 7 to Figure 12 shows the spray from nozzle having an half spray angle 30° for different injection pressures.

Figure 7. Spray for α = 60° and ΔP = 18 bar

Figure 8. Spray for α = 60° and ΔP = 15 bar

Figure 9. Spray for α = 60° and ΔP = 12 bar

Figure 10. Spray for α = 60° and ΔP = 9 bar

Figure 11. Spray for α = 60° and ΔP = 6 bar

Figure 12. Spray for α = 60° and ΔP = 3 bar

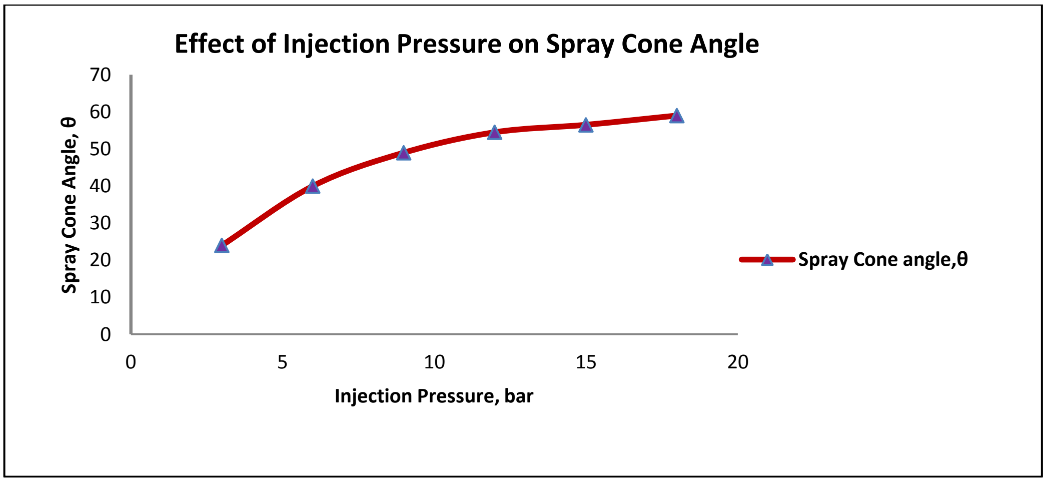

Figure 13. Effect of Injection Pressure on Spray Cone Angle

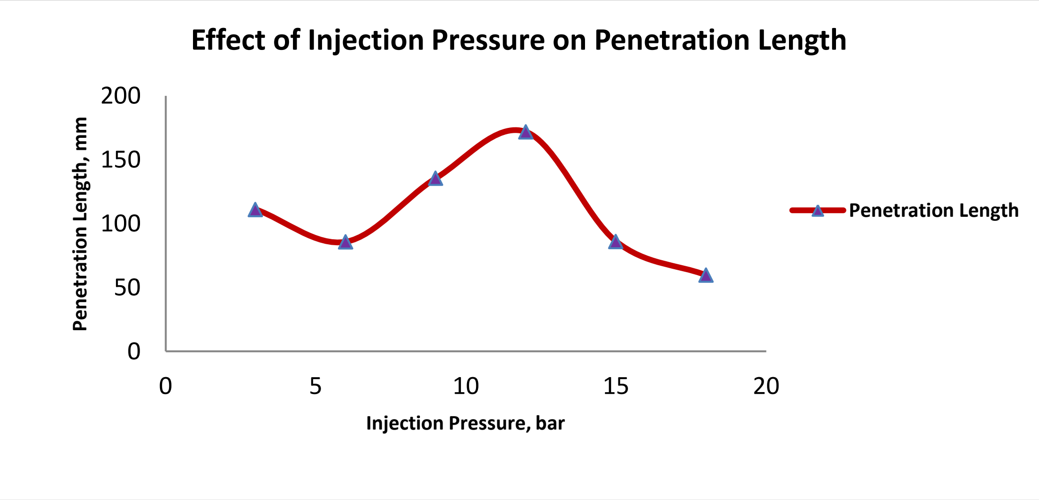

Figure 14. Effect of Injection Pressure on Penetration Length

Figure 13 advocates that as the injection pressure increases from 3 bars to 18 bars in the step of 3 bar the spray cone angle of designed pressure swirl nozzle increases and reaches near 60^o at designed pressure of 18 bars. From Figure 14, it can be concluded that as the injection pressure increases from 3 bar to 18 bar in the step of 3 bar the penetration length decreases from 3 bar to 6 bar but during that proper spray of kerosene does not take place and also it does not create enough pressure for breakup of liquid into small drops. After 6 bar up to 12 bar further increment found in the penetration length due to breakup of liquid film into small drops up to 12 bars. From 12 bars to 18 bar as the enough pressure is provided, spray cone angle increases and penetration length decreases [11, 12, 13]. From Figure13 and Figure 14 it can be seen that the shortest penetration length and maximum spray angle achieved at designed injection pressure 18 bars. This type of behaviour of pressure swirl atomizer is basically related to fluctuation of pressures and spray cone angles.

V. CONCLUSIONS

The design of pressure swirl nozzle is carried out at injection pressure of 18 bar. The experiments of penetration length and spray cone angle are carried out with the injection pressure from 3 bar to 18 bar with the step of 3 bar. Experiments suggest that at 3 bar, the penetration length and spray cone angle are minimum and also that at 3 bar liquid film is not breaking into small droplets. From 3 bar to 18 bar as injection pressure increases the cone angle also increases and penetration length decreases but except from 6 bar to 12 bar penetration length increases due to liquid film starts breaking in small droplets. So the maximum angle achieved is nearly 60^o and minimum penetration length is achieved nearly 62mm at designed injection pressure of 18 bars. It can be concluded that the designed pressure swirl atomizer operating at 18 bar pressure can be used for Annular Type Gas Turbine Combustion Chamber using Kerosene Type Fuel. As the part of future work the same pressure swirl atomizer experimental investigation will be carried out for effect of injection pressure on flame length with different liquid fuels.

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