DESIGN AND EXPERIMENTAL INVESTIGATIONS OF PRESSURE SWIRL ATOMIZER OF ANNULAR TYPE COMBUSTION CHAMBER FOR 20 kW GAS TURBINE ENGINE

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ABSTRACT

The present work describes the design of pressure swirl atomizer nozzle for half spray cone angle of 30° and outlines the complete detail of experimental setup, which includes the incorporation of penetration length measurement along with spray cone angle. Because the spray penetration is having 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 cause 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 are therefore essential to sound engine design. The spray angles produced by pressure swirl atomizer have special importance in their applications to combustion system. In gas turbine combustor, spray angle has strong influence on ignition performance, flame blowout limits and the pollutants, emissions of unburned hydrocarbons and smoke. The drop diameter is measured in SEM by collecting drops on the slides coated with magnesium oxide. The setup for drop collection is also developed.

Keywords: Annular Combustor, Penetration length, Pressure swirl atomizer, 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 informations 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 Fig.1. 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° to almost 180°, 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.
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, $\alpha$, $\Delta P$, $\rho$ and $\nu$. 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 $\alpha$ from Fig. 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 $\varepsilon$ and Spray Angle $\alpha$ on Geometric Constant of Swirl Atomizer $k$ [8]

$$G = \rho Q = C_D A_0 \sqrt{2 \rho \Delta P} \quad (1)$$

$$d_0 = \frac{4G}{\pi C_D \sqrt{2 \rho \Delta P}} \quad (2)$$

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

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

$$K = \frac{2 R d_0}{i d_p^2} \quad (3)$$

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.
In the case of orifice with a shape other then 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

\[
Re = \frac{\nu_p d}{\vartheta}
\]  

(5)

Where, \(d\) is the equivalent diameter of the orifice

\[
\frac{\pi d^2}{4} = i \left( \frac{\pi d_p^2}{4} \right) \quad \text{and} \quad \nu_p = \frac{4G}{\rho i \pi d_p^2}
\]

So (5), can be reformed as

\[
Re = \frac{4G}{\pi \rho \vartheta \sqrt{i d_p}}
\]  

(6)

Friction coefficient \(\lambda\) follows from the formula

\[
\log \lambda = \frac{25.8}{(\log Re)^{2.58}} - 2
\]  

(7)

The value of \(\lambda\) 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:

\[
\frac{B^2}{i} - K \leq \frac{2}{\lambda} (\Phi^{1.5} - 1)
\]  

(8)

Where \(\Phi = \) 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 \(\alpha\) 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

\[
\varphi = \frac{A_p}{A'_p} = \left( \frac{d_p}{d_p'} \right)^2 \quad \text{hence} \quad d_p' = \frac{d_p}{\sqrt{\varphi}} \quad (9)
\]

The contraction coefficient is assumed to be \( \varphi = 0.85 - 0.90 \).[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

\[
D_s = 2R + d_p'
\]

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 \( l_p \) 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 \( \alpha \). For \( K_\lambda < 4 - 5 \), \( l = (0.5 \text{ to } 1.0) \, d_0 \)[8] is recommended and for \( K_\lambda > 4 - 5 \), \( l = (0.25 \text{ to } 0.5) \, d_0 \)[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 \( 7.199 \times 10^{-3} \, \text{kg/s} \), 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>
<thead>
<tr>
<th>TABLE 1 Summary of design parameters for pressure swirl nozzle</th>
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<tbody>
<tr>
<td><strong>Design Data</strong></td>
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<tr>
<td>Discharge Orifice Diameter, ( d_0 )</td>
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<tr>
<td>Distance of Tangential Inlet Port from Central Axis, ( R )</td>
</tr>
<tr>
<td>Number of Tangential Inlet Ports, ( i )</td>
</tr>
<tr>
<td>Tangential Inlet Port Diameter, ( d_p )</td>
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<tr>
<td>Swirl Chamber Diameter, ( D_s )</td>
</tr>
<tr>
<td>Length of Swirl Chamber, ( l_s )</td>
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<tr>
<td>Length of Inlet Port, ( l_p )</td>
</tr>
<tr>
<td>Length of Discharge Orifice, ( l )</td>
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</table>
III. Test Setup for Penetration Length and Spray Cone Angle Measurement

The experimental setup is developed for the measurement of various spray characteristics for different nozzle. The setup is equipped to measure the spray penetration length and spray cone angle. Fig. 5 shows the schematic diagram of the experimental setup.

Based on maximum flame diameter and flame length [9], the test chamber dimensions for mass flow rate of $7.199 \times 10^{-3}$ 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 of the spray. Fig. 6 shows the test chamber.

Figure 4 Photographic View of Designed Nozzle

Figure 5 Schematic Diagram of Experimental Setup
IV. **TEST SETUP FOR DROP DIAMETER MEASUREMENT**

The drops are collected on the slides coated with magnetism oxide layer. The setup for the drop collection is the base of the stand is made of square M. S. plate. Its size is 300 mm X 300 mm. The distance between the base plate and the injector tip is 100 mm. This is based on the theoretical calculation of breakup length [10]. The holder for the atomizer is provided above the center of the plate. The base plate and the atomizer is separated by another plate which slides between atomizer and sampling slides on the base. The drops collected on the slides are analyzed in the Scanning Electron Microscope, Hitachi make model: 3400N.

V. **RESULTS AND DISCUSSIONS**

The experimental results shows the effect of pressure on penetration length, cone angle and drop size measured by SEM.

A. **Measurement of Penetration Length and Cone Angle**

The experimental setup for the measurement of spray penetration length and cone angle is shown in the Fig. 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 measure using high speed camera (Nikon D 60). For the easy measurement, the grids of illuminated strips of size 5cm × 5cm are attached on the acrylic sheet. Fig.7 to Fig. 12 shows the spray from nozzle having an half spray angle 30° for different injection pressure.
B. Measurement of Drop Size

The position of slides under the nozzle at the time of experiments. The slides are placed at the centre and at the periphery of the spray. The nozzle of spray cone angle of 60° is set on the testing stand and the slide with magnesium oxide coating is placed under the slider. Once the spray is fully developed, the slides are made open for a small interval of time and again it is covered with slider. The drop samples are accumulated on the slides. The slides are taken away carefully and tested under SEM (Scanning Electron Microscope). Due to non-conductive material the slides are first coated using an Ion Sputter. The images of that drops are captured and their diameters are measured in SEM. Fig. 13 to 14 give SEM images for nozzle having half cone angle of 30°.
From Fig. 13 to Fig. 14 it can be concluded that for the lower injection pressure, drop diameter was found to be bigger than that at higher pressure. The drop diameter ranges from 330 microns for lower injection pressure of 3 bar to 40 microns at higher injection pressure. With pressures higher than 12 bar it was difficult to find the drop diameter as the slides were washed out, probably due to very high velocities emerging from the nozzle exit.

**Figure 15** Variation of Half Spray Cone Angle with Pressure

From Fig. 15 and Fig. 16, it can be concluded that as the injection pressure increases spray cone angle tends to increase, but above the injection pressure of 15 bar, the spray cone angle as measured experimentally decreases slightly. The penetration length pattern is not uniform. There is an increase in the penetration length up to 12 bar injection pressure with the exception of 6 bar injection pressure, where the penetration length decreases. But the shortest penetration length was found to be at 18 bar injection pressure. This type of behavior of pressure swirl atomizer is basically related with fluctuating pressures and related spray cone angles.

**Figure 16** Variation of Penetration Length with Pressure
VI. CONCLUSION

The measurement of spray penetration length, spray cone angle and the spray droplet size are carried out on the experimental setup developed during this work. The penetration length tends to increase up to injection pressure of 12 bar with an exception of 6 bar. But at designed injection pressure of 18 bar, the penetration length is the shortest. The spray cone angle is lowest at 3 bar pressure, but thereafter increases at higher pressure. The highest spray cone angle is achieved at a pressure of 15 bar. But thereafter a slight decrease in cone angle is observed. The drop diameter decreases with increase in injection pressures, with drop diameter ranging from 330 microns for lower pressure of 3 bar to 40 microns at higher injection pressure.

It could 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.

REFERENCES