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INVESTIGATIONS OF A CIRCULAR JET WITH SWIRL

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ABSTRACT

Swirl flow in a circular jet was created by supplying compressed air to the nozzle reservoir which leaves through an annular gap. The air from the gap entrains air from the inlet and the combined the flow follows the curved surface of the nozzle due to the coanda effect. The flow continues to swirl after leaving the nozzle. Quantitative investigation of a swirl nozzle performance indicated that the flow was not symmetrical about the geometric centre of the nozzle and that a modified swirl number should be used to define the degree of swirl. Increasing the nozzle annular gap from 0.1 mm while maintaining a constant supply mass flow rate gives a "top hat" velocity profile. The maximum axial velocity occurred when the profile was "bullet" shaped for a gap of 0.15 mm, which showed a decrease as the gap was increased from 0.15 mm. The modified swirl number decreased as the gap was increased from 0.1 mm. The qualitative investigation involving flow visualisation indicated that the flow had an intense swirl motion. The intensity of the swirl can be reduced by supplying a secondary air supply at the nozzle inlet. .

Key words: swirl, coanda effect; entrainment

Notation

- D nozzle exit diameter
- G_x axial thrust
- G_φ angular momentum
- p pressure
- r radial co-ordinate
- R orifice radius
- S swirl number
- S' modified swirl number
- U axial velocity component
- W tangential velocity component
- ρ density of air

INTRODUCTION

Swirl flow, also referred to as spiral flow, has a significant angular velocity component in addition to radial and axial velocity components of non-swirl flow. The angular velocity component increases the radial pressure gradient away from the centre line of the flow and the axial pressure gradient away from the nozzle exit. When these pressure gradients are sufficiently large the flow will have an internal recirculation zone (IRZ). Beer and Chigier [1] have conducted a detailed investigation of the effects of swirl flow and IRZ in combustion nozzle flows. Beer and Chigier demonstrated the introduction of swirl changes the characteristics of a flow and that the Reynolds number based on the nozzle internal diameter alone cannot separate a non-swirl flow from a swirl flow as the Reynolds number does not consider the angular velocity component. They defined the swirl number (S) to describe swirl flow as

$$S = \frac{G_\varphi}{G_x R} \qquad 1$$

where

$$G_\varphi = \int_0^R (Wr)\rho U 2\pi r dr = const.$$

$$G_x = \int_0^R U\rho 2\pi r dr + \int_0^R p 2\pi r dr = const.$$

This definition of S assumes that the flow is axisymmetric. Horii [2] observed that the flow from a swirl nozzle was not axisymmetric and could not use the previous equations to determine S. S was replaced with a modified swirl number S', defined as

$$S' = \frac{\frac{1}{2}(W_{max}/U_{max})}{1 - \frac{1}{4}(W_{max}/U_{max})^2} \qquad 2$$

Beer and Chigier use the swirl number to divide swirl flows into flows with weak and strong swirl. Weak swirl flows have a swirl number less than 0.6 and strong swirl flows with swirl number greater than 0.6 generate an IRZ.

Swirl flows with the angular velocity component are useful in cyclone separators to separate heavier particles from lighter particles. Some combustion nozzles use swirl flow with an IRZ [1] to thoroughly mix fuel and air to increase the combustion efficiency. Combustion nozzles generate their swirl by supplying part or all of their air tangentially into the nozzle or using mechanical devices like fixed vanes or a rotating propeller to generate swirl. Horii [2][3] used the longevity of the swirl flow to pass fibre optic cables through pipelines; our nozzle (Figure 1) is similar to the nozzle used by Horii. Compressed air is supplied through two diametrically opposite ports on the nozzle into a reservoir and as the air leaves through the annular gap it entrains air from the inlet. The combined flow follows the curved surface of the nozzle due to the coanda effect and continues to exhibit a swirl nature after leaving the nozzle.

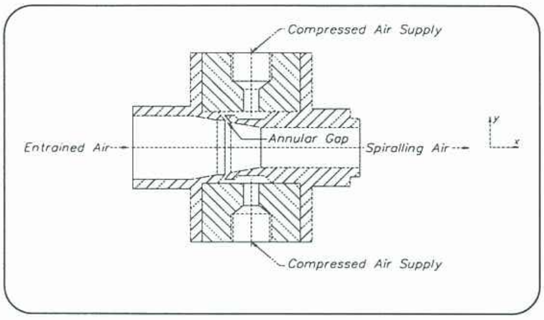

Figure 1: Swirl Nozzle

The aim of this report is to investigate the flow symmetry, the effect of changing the annular gap as well as employ flow visualisation to study the flow in a swirl nozzle. The flow visualisation also included another swirl nozzle that has its compressed air supply ports enter the reservoir tangentially (Figure 2). The modified nozzle is currently being used for further investigations.

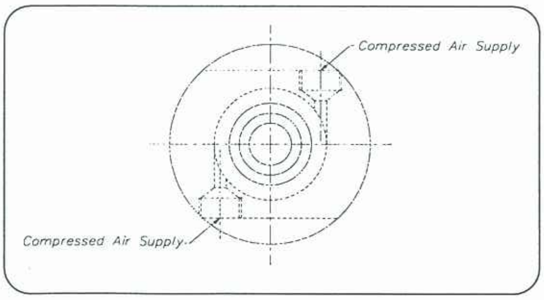

Figure 2: Modified swirl nozzle

EXPERIMENTAL CONDITIONS

The flow characteristics were quantitatively determined by measuring the mean velocity distribution using a yaw probe (also referred to as a three hole pitot tube) with the static pressure taken at the wall of the nozzle exit. The advantage of the yaw probe over the two hole pitot tube is that the yaw probe can measure both the axial and tangential velocity components simultaneously.

The flow symmetry was investigated by measuring the mean axial and tangential velocity profiles along two perpendicular axes 1 mm downstream of the nozzle exit. The mean velocity profile measurements were made at 1 mm intervals along an axis that was perpendicular to the axial direction of the flow. The nozzle had a 1.55 mm annular gap and mass supply flow rate of 0.0042 kg/s.

The influence of the annular gap was investigated by measuring the velocity profile 1 mm downstream of the nozzle when the annular gap was 0.1 mm and the supply flow rate was 0.0033 kg/s. The velocity profiles were remeasured with the supply flow rate fixed at 0.0033 kg/s but with an annular gap that was increased at 0.05 mm steps until it was 0.3 mm.

Several flow visualisation techniques were investigated including smoke, inserting a assorted threads into the nozzle inlet and supplying water to the nozzle compressed air supply ports. The main flow visualisation technique involved inserting a fine cotton thread into the nozzle inlet. The thread enveloped flow leaving the nozzle displayed the swirl characteristics of the flow. The thread was illuminated by two electronically linked General Radio Company Strobotac Strobes that delivered a single pulse of light. The flow visualisation was recorded on a high speed video camera as well as an 8 mm video camera.

DISCUSSION

The distribution of the mean axial velocity (U) and mean tangential velocity (W) against y/D, shown in figures 2 and 3, indicates that the axial and tangential velocity profiles of the swirl flow are not symmetric with respect to the geometric centre line of the nozzle. This confirms the result of Horii, Matsumae, Cheng, Takei and Hashimoto [4] but their tangential velocity profile was different to the present result. Beltagui and MacCallum [5] suggest three possible causes of flow asymmetry, namely:

a) machining or assembling asymmetry that biases the flow direction,
b) coanda effect,
c) vortices between the main forward flow and the IRZ. These vortices precess on an axis inclined to the flow or on the axis of the flow.

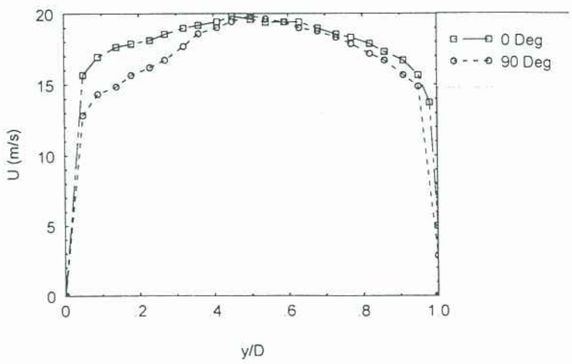

Figure 2: Axial velocity profiles in two perpendicular axes

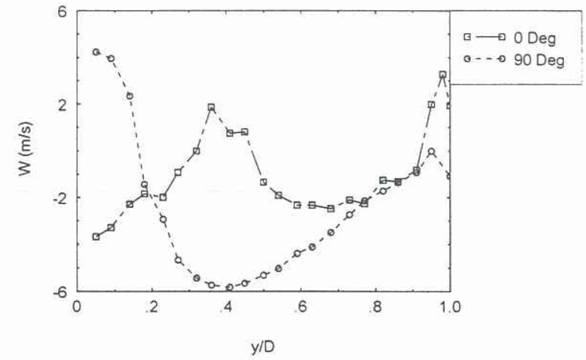

Figure 3: Tangential velocity profiles in two perpendicular axes

The effect of the annular gap on the axial and tangential velocity profiles, plotted in figures 4 and 5, indicate that the gap has a significant influence on the velocity profiles. The minimum gap of 0.1 mm showed an axial velocity profile with two peaks and as the gap was increased the profile became more uniform. The tangential velocity decreased as the annular gap increased. The maximum axial velocity increased as the gap is increased up to 0.15 mm and then drops when the gap was 0.2 mm. The axial velocity increased again at a gap of 0.25 mm and then decreased.

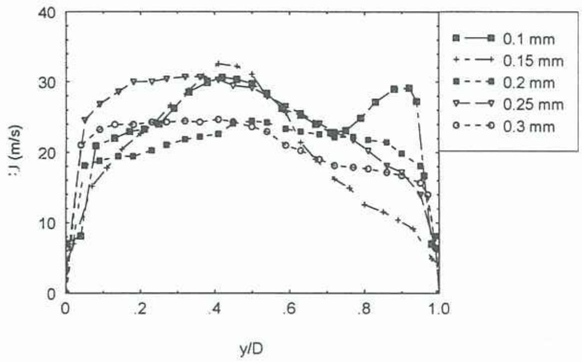

Figure 4: Influence of annular gap on axial velocity

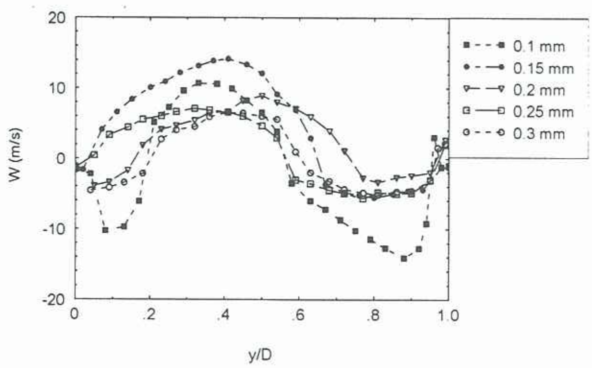

Figure 5: Influence of annular gap on tangential velocity

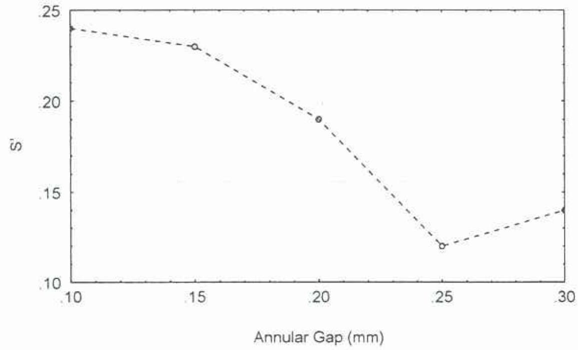

Figure 6: The effect of annular gap on S'.

As the flow from the nozzle is asymmetric the modified swirl number was calculated for each gap (Figure 6). The smallest annular gap had largest swirl number of 0.24 which decreased as the gap was increased to 0.25 mm. The minimum swirl number at an annular gap of 0.25 mm coincided with the second maximum axial velocity peak. The swirl number when the gap was 0.3 mm was slightly larger than the number when the gap was 0.25.

The initial flow visualisation technique involved drawing evaporated oil smoke into the nozzle inlet and observing the flow leaving the nozzle exit. The smoke partially condensed in the nozzle and what passed through did not clearly display the swirl nature of the flow. The next option was to insert a fine thread or fibre into the flow and observe its movement. Several cotton threads, nylon thread and horse hair were inserted in the flow to find the optimum material that could be used and was most visible under the illumination of the strobes. Cotton thread performed better than the horse hair that was not easily seen and the nylon thread that would become tangled. When the cotton thread inserted into the flow of swirl nozzle it indicated that the produced a definite swirl flow (Figure 7). A small amount of compressed air flow, introduced at the inlet of the nozzle, increased the wave length of swirl flow (Figure 8) and the swirl shape was more distinct. The compressed air decreased the tangential to axial velocity ratio which directly decreased the swirl number of the flow. The addition of a secondary flow could be used to control the swirl of the flow below its maximum swirl number. Further studies are in progress to investigate the influence of secondary flow.

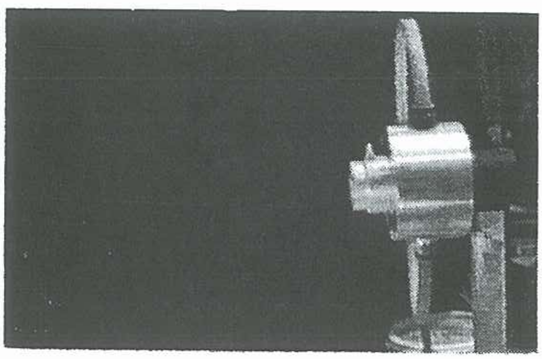

Figure 7: Cotton thread inserted into the swirl flow

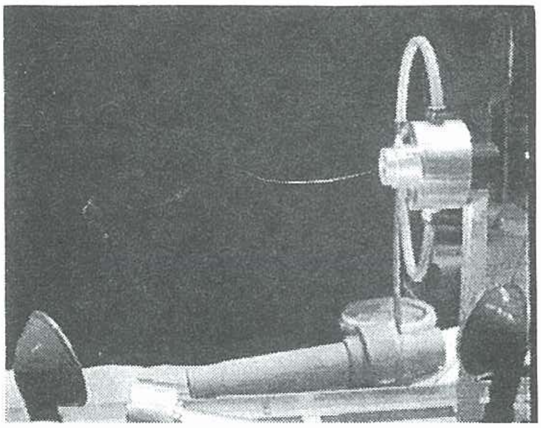

Figure 8: Secondary flow introduced at the nozzle inlet.

The modified swirl nozzle created a more intense swirl pattern than the first nozzle (figures 9 and 10). More detailed measurements are currently being conducted on the modified nozzle.

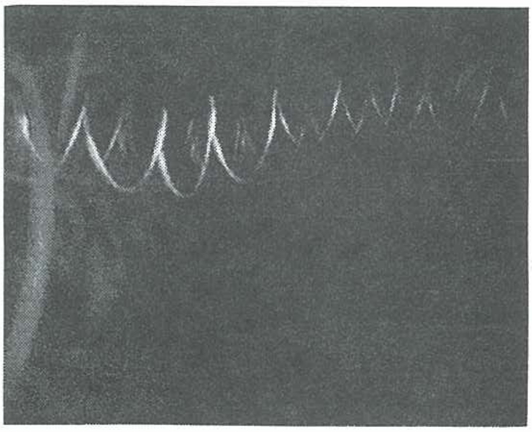

Figure 9: Front view of the cotton thread leaving the modified swirl nozzle.

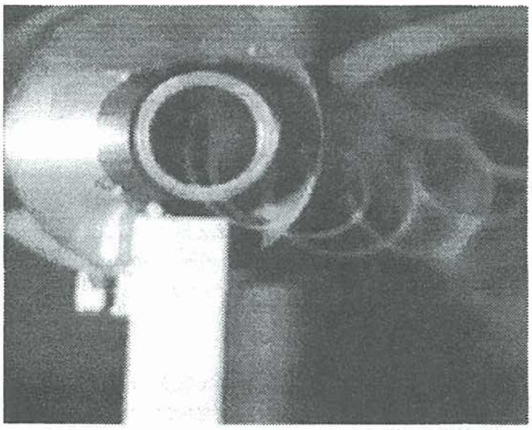

Figure 10: Side view of the cotton leaving the modified swirl nozzle.

Non-uniformities in the first nozzle annular gap can be observed by supplying water to the compressed air supply ports. The water was supplied at mains pressure to the nozzle with the annular gap closed. Water still flowed through several sections of the gap indicating the annular gap was not uniform. The effect of the variation in the annular gap on the swirl flow is not completely known but Beltagui and MacCallum [5] suggested that a variations in a swirl nozzle construction could make the flow asymmetric.

CONCLUSION

The flow from the swirl nozzle was not symmetric which meant the swirl number suggested by Beer and Chigier could not be used. The asymmetry may have been caused by the non-uniformities in the annular gap which were observed when water was passed through the supply ports of the nozzle with the gap closed. The modified swirl number was used to define the degree of swirl in the flow. The swirl number decreased from 0.245 as the annular gap increased. This swirl number indicates the flow has weak swirl since it less than 0.6. The maximum axial velocity occurred when the gap was 0.15 mm.

The swirl nozzle was observed to create a swirl flow. The intensity of the swirl can be reduced by the addition of a secondary air supply at the nozzle inlet . Although the swirl nozzle with diametrically opposite inlets displays a definite swirl flow, the modified nozzle creates a more intense swirl flow.

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