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An Experimental Investigation of Swirl Angle in a Horizontal Round Tube by Flow Visualization Method

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Key words : Swirl angle, Swirl intensity, Swirl number, vortex core

Abstract

Swirling air flow in a horizontal round tube was experimentally studied for its visualization. The present investigation deals with swirl angle, flow visualization studies and accompanying vortex core behavior by using oil smoke and a hot wire anemometer for Re = 40,000 and 50000 at X/D = 41, 59 and 71. In the swirl air flow, a vortex core was formed at high swirl intensity along the test tube. The swirl angle and the vortex core depended on the swirl intensity along the test tube. The results of swirl angles measured by flow visualization and hot wire reasonably agree with those of previous studies.

Nomenclature

D : inside diameter of the test section tube,
E : instantaneous voltage of hot wire,
H : yaw factor,
K : pitch factor,
L : axial distance between the exit of the swirl chamber and the inlet of the test section tube,
P : pressure,
Re : Reynolds number
s : hot wire calibration sensitivity factor,
U, V, W : time averaged axial, radial and tangential velocity components,
$\overline{U}, \overline{V}, \overline{W}$: mean velocities,
u, v, w : fluctuating velocity components,
X : axial coordinates
y : radial position or distance from the wall
α, β : angle defined for how wire calculation
θ : swirl angle

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1. Introduction

During the past three decades or so, the characteristics of turbulent swirling flow have been studied extensively because of their scientific importance.

It is well known that swirling flow improves heat transfer in tube flow. The reason for this is due to the effect of streamline curvature associated with the tangential velocity component, and so the path of the curved streamline is longer than the rectilinear path without swirl. Therefoe, the fluid particles near the wall will transport more energy either to or from it. A detailed invstigatigation of swirling flow in an axisymmetric tube has been undertaken to measure swirl angle and flow visualization.

One of the most important studies of turbulent swirl flow was carried out by Nuttall[1]. He was one of the first to observe the flow characteristics of swirling flow in a circular

tube by using dye injection. The early investigations such as those of Binnie et al.[2], Talbot[3], Robert et al.[4] and Cassidy et al.[5] used flow visualization techniques to confirm the existence of flow reversal regimes.

All subsequent experimental observations have been made to investigate this flow structure using different observation techniques. Others such as Nuttall[1], Binnie et al.[2], and Sparrow et al.[6]used flow visualization techniques similar to Nuttall's[1] early experiments. Later, investigations by Rose[7], Roberts et al.[4], Wolf et al.[8]and Wesk et al.[9] used more sophisticated measurement techniques such as hot wire anemometry.

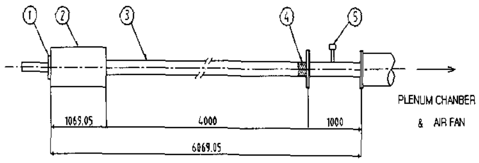
However, far, the most useful definition of swirl was derived from the investigation of Hay et al.[10] and Kawaguchi et al.[11]. They suggested a swirl number that reflected the local state of the decaying swirl. Also, Hay et al.[10] reported that the radius of vortex core is 0.4R. These works are summarized in table 1.

This study deals with swirl angle in the horizontal round tube, flow visualization studies and vortex core by using oil smoke and a slanted hot wire probe for Re= 50000 at X/D = 41, 59 and 71. Finally, the main conclusions drawn from these investigations are discussed in comparison with Sparrow et al.[6] and Hay et al.[10] is research.

2. Experimental Apparatus

Fig.1 shows the isothermal apparatus. Air was drawn through a swirl generating chamber, the test tube working section, through flow metering and main plenum chamber by a centrifugal fan. The isothermal test section was of 50.8 mm inside diameter with a wall thickness of 6.35mm and length of 4m, and was manufactured from plexi glass.

A method was needed for measuring static pressures along the length of the test section. Of those examined, the simplest in terms of easiness of design, construction and intensity of swirl was considered to be that of Sparrow and Chaboki[6] and therefore, it was adopted for the present investigation.



No.	Apparatus	Sizer	Materials
①	Swirl generator	Φ140×249.5	Plexiglass
②	Swirl chamber	Φ228.6×1069	Plexiglass
③	Test tube	Φ50.8×4000	Plexiglass
④	Honey comb		Oil paper
⑤	Multi-pitot tube	Φ50.8	Steel

Fig. 1 Arrangement of Experimental Apparatus.

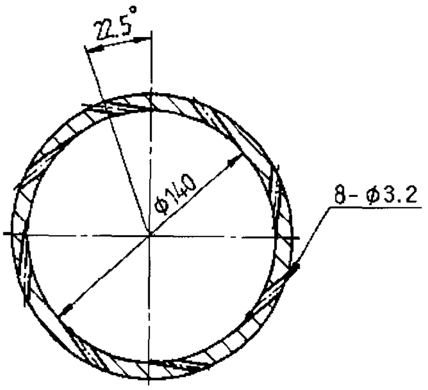


Fig. 2 Cross Section View through Swirl Generator.

Table 1 Summary of Previous Study on Swirling Flow using Visualization Technique.

No.	Author	Type Flow	Working Fluid	Range of Reynold Number	Measured Paramete	Used Materials	Remark
1	Nuttall 1953	Swirl	Water	10,000~30,000	Nagative axial velocity	Dye	
2	Talbot 1954	Swirl	Water	2,700	Axial velocity	Dye filament	
3	Binne 1957	Swirl	Water	60~260	U, V	Colour injection	
4	Harvey 1963	Swirl	Air		Vortex Breakdown	Titanium Tetrachloride	
5	Robert 1965	Swirl	Air Water	60,000 ~ 75,000	Reversal flow	Dye	
6	Kerr 1965	Swirl	Air Water		Reversal flow	Polystyrene	
7	Cassidt 1970	Swirl	Air		Reversal flow	Tobacoo Smoke	
8	Escudier 1980	Swirl	Water	4,800	Reversal flow	Dye	
9	Wan 1982	Swirl	Oil, Air	250~500	Vortex Breakdown	Aluminum Paint	
10	Sparrow 1984	Swirl	Air	9,000~43,500	Swirl Angle	Oil lampblack	
11	Hallett 1984	Swirl	Air	67,000	Vortex Breakdown	Smoke	
12	Clayton 1984	Swirl	Air	9,000~60,000	Swirl Angle	Tuft	
13	Escuier 1984	Swirl	Air	20,000~60,000	Swirl Angle	Oil smoke	
14	Chang 2003	Swirl	Air	20,000~60,000	Swirl Angle	Oil smoke	

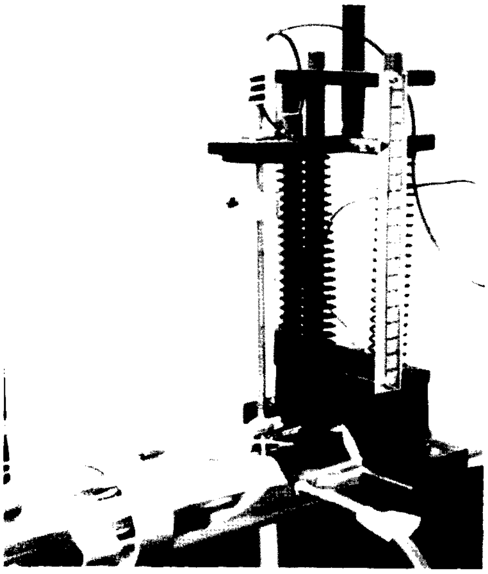


Fig. 3 Hot wire Probe Orientation in the Test Rig for Velocity and Swirl Angle Measurement.

The essential features of the swirl generator is shown in Figure 2.

The figures show that the generator was constructed by milling 159.5mm long grooves to a depth 6.35mm and a width of 3.2mm longitudinally in the outer surface of the perspex cylinder parallel to its axis.

The slots were spaced equi-distantly at 45 degrees around the circumference of the cylinder.

In each groove a row of holes was drilled tangentially to the inner wall of the cylinder.

For all flow interrogation, the appropriate measurement probe could be located accurately in the cross-section plane of the tube by installing it in traversing mechanism as shown in Fig. 3. Any probe could be rigidly bolted to this apparatus during any particular experiment. The radial position of the probe in the working section was altered using a micrometer screw head, which was manufactured from a 25mm screwed rod. Finally a protractor gauge, calibrated in one degree intervals, was bolted to the steel upper plate. This contained a bushing and pointer arrangement into which any probe could be installed, thus allowing for any angular position of probe to be selected.

In order to study the purely fluid mechanics effects of swirling flow, the isothermal flow apparatus was used for the flow visualization test.

3. Method of Velocity Measurements

Hot wire anemometry was used for the bulk of the isothermal flow velocity measurement. The implication for this in swirl flow is that measurements are usually confined to a small sample of the tube, and hence the full influence of the decay cannot be investigated, as is intended in the present study.

A far more convenient method of such measurement was found to be an inclined single wire probe i.e. where the sensor is inclined at 45 degree to the probe axis. The hot wire response equations necessary for the determination of the flow parameters mentioned above are derived from equation (1).

$$\begin{aligned} E^2 \ (\beta,\alpha)/s^2 = \{ & (V+v)\cos\alpha + [(U+u)\cos\beta \\ & - (W+w)\sin\beta]\sin\alpha\}^2 + H^2\{[(U+u)\cos\beta \\ & - (W+w)\sin\beta]\cos\alpha \\ & - (V+v)\sin\alpha\}^2 + K^2[(U+u)\sin\beta \\ & + (W+w)\cos\beta]^2 \end{aligned} \tag{1}$$

From equation (1), the angle α and β are changed with H and K, the mean and fluctuating velocities are calcualted along the test tube.

4. Experimental Results and Discussion

4.1 Velocity profiles

The axial velocity distributions for L/D=0, 8 and 16 at a Reynolds number of 50,000 are shown in Fig. 4.

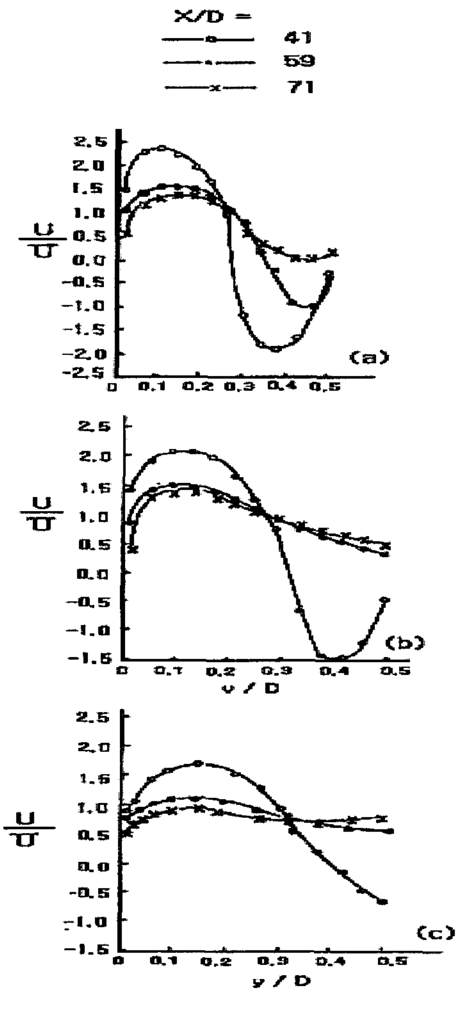


Fig. 4 Experimental Axial Velocity Distributions across the Test Tube with Swirl for Re = 50,000 at (a) L/D = 0, (b) L/D = 8 and (c) L/D = 16.

The sequence of velocity distributions clearly demonstrates that the flow reversal becomes diminished and finally disappears with axial distance from the inlet, as the swirl is reduced (i.e. as L/D increased)

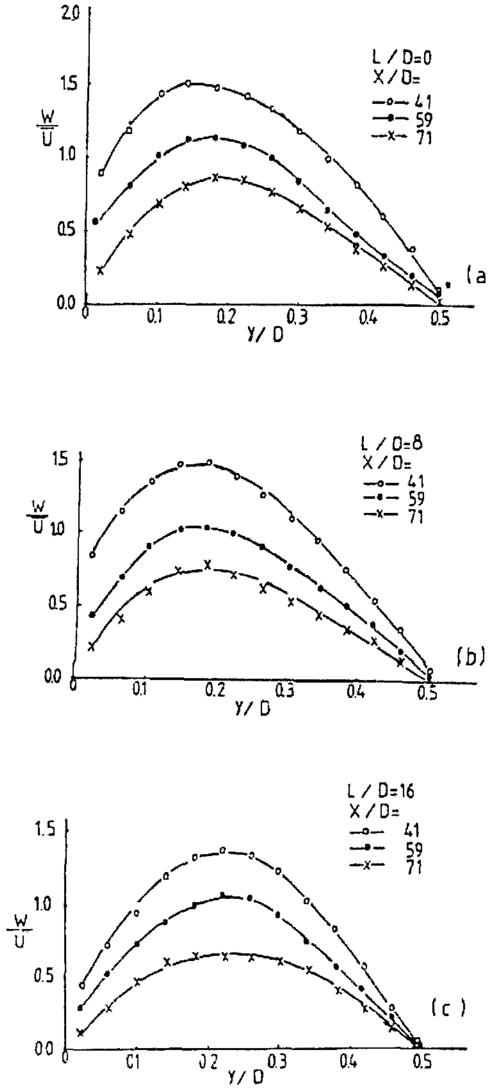


Fig. 5 Experimental Tangential Velocity Distributions across the Test Tube with Swirl for Re = 50,000 at (a) L/D = 0, (b) L/D = 8 and (c) L/D = 16.

The effect of increasing the swirl intensity and Reynolds number is to move the position of maximum velocity towards the tube wall and produces more flow reversal. In general, the shape of the presented velocity profiles is similar to those obtained by Blum et al.[12], Chang et al.[13], Kreith et al.[14] and Linderstrom et al.[15]

Fig. 5 shows the dimensionless variations of the tangential velocity components for the same range of swirl intensity and Reynolds number. Inspection of the figure shows that, as would be expected, the value of the tangential velocity component decreased with swirl intensity, Reynolds number, and axial distance.

4.2 Flow Visualization

As well as using the information from the velocity fields to quantify swirl, several limited flow visualization tests were carried out in an attempt to gain further insight into the nature of swirl flow. However, because of the high level of turbulent mixing in the flow, it was very difficult to photographically record any experiments. Two distinctive features were observed, that of a central core and the 'flow angles' at the test tube surface. Photographs of the phenomena are shown in Figures 6(a) and (b).

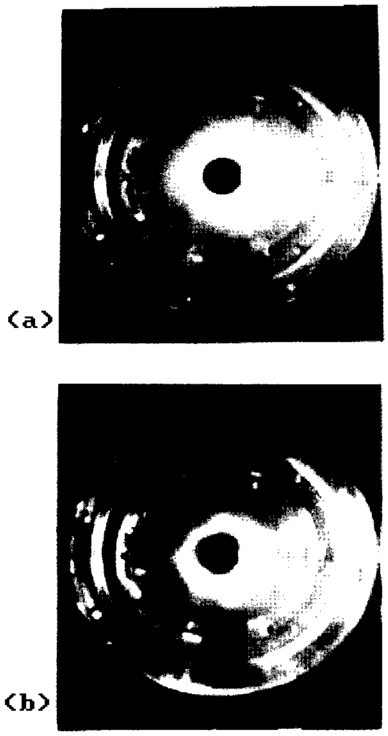


Fig. 6 Distribution of Swirl Flow and Vortex Core in the Swirl Chamber for (a) L/D = 14 and (b) L/D = 16.

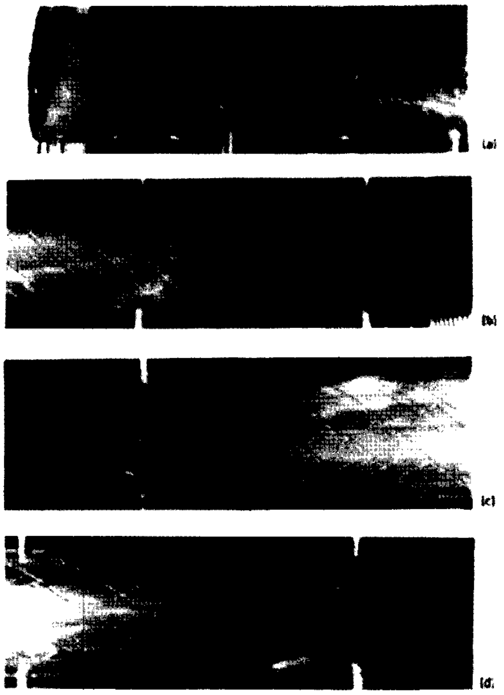


Fig. 7 Flow Visualization Photographs of Swirl Angle in the Test Tube for L/D = 8 at Reynolds Number 50,000.

The existence of the central vortex core was particularly noticeable in the upstream section of the tube where some flow reversal occurred, as indicated by the axial velocity distributions

During this flow visualization test it was observed that some of the water based liquid used to generate the smoke had condensed. This was deposited on the inside of the tube wall in the form of droplets which followed the path of the swirling flow.

An examination of the flow was carried out at L/D = 8 and a Reynolds number of 50,000 and are shown in Fig.7 and Fig. 8. The photograph verifies the axisymmetry of the flow as can be seen from the nature of the various trajectories of the droplets.

Fig. 8 Flow Visualization Photographs of Swirl Angle in the Test Tube for L/D = 8 at Reynolds Number 50,000.

Similar results were obtained by Sparrow et al.[6] who injected an oil and lamp black mixture onto a white plastic, self-adhering contact paper laid on the inside of the tube. By removing the paper, the angle made by the flow relative to the tube axis could be measured. In the present experiment, these angles were evaluated by placing a clear plastic sheet over the outside of the tube, tracing the streak lines and then measuring the angle in a similar manner to that of Sparrow et al.[6]. The movement of the droplets was, of course, due to the shear stresses exerted by the flow at the tube wall. The angle between the droplet path and the axial direction is the result of the interaction between the tangential and axial components of the wall shear stresses at the location considered.

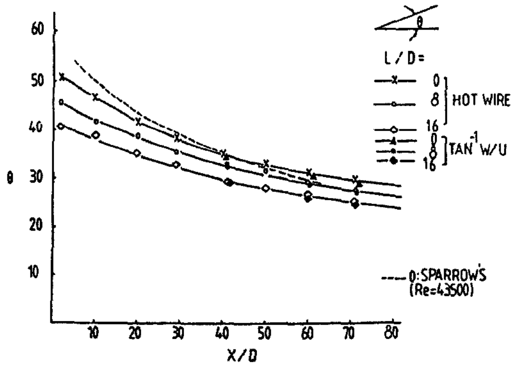


Fig. 9 Swirl Angle Distributions at L/D = 0, 8,16 for Re = 50,000.

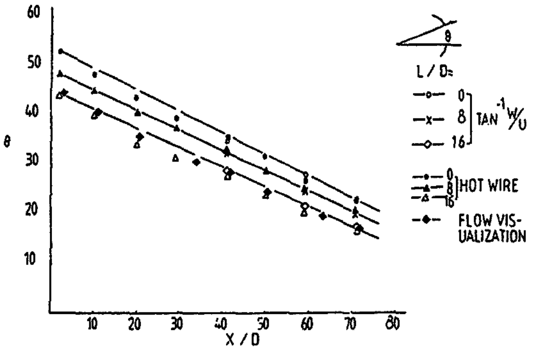


Fig. 10 Swirl Angle Distributions at L/D = 0, 8, 16 for Re = 50,000.

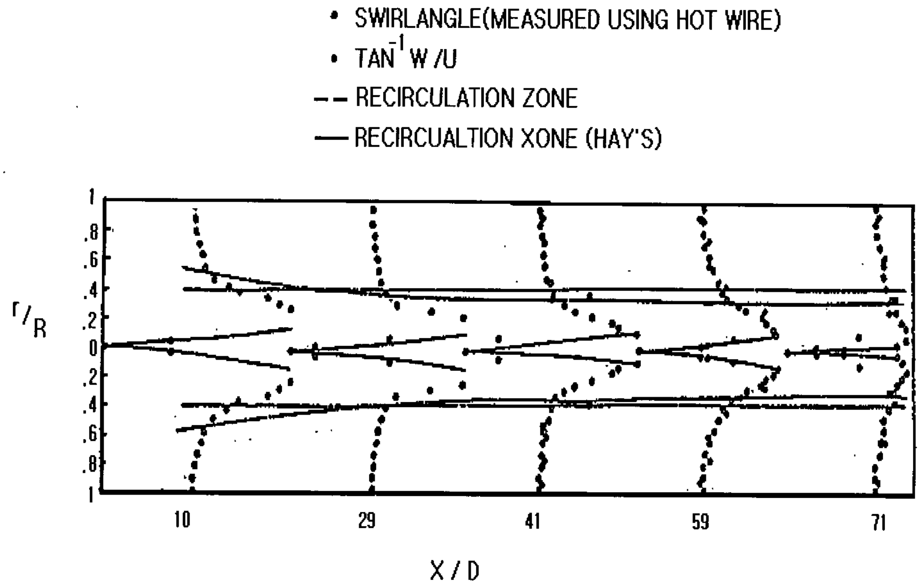


Fig. 11 Distributions of Swirl Angle and Recirculation Zone Along the Test Tube for Re = 50,000.

4.3 Flow Angle Measurements

Included in Figure 9 and Figure 10 are the curve derived from the results of Chaboki subsequently published by Sparrow et al.[6], which demonstrates this experimental decay of the swirl angle.

As can be seen, the above expression slightly over predicts. This is probably due to the fact that Chaboki derived the expression based on limited ranges of L/D(only 2) and Reynolds numbers (9,000 to 43,000). It is also pointed out that the ratio of the diameters of the swirl chamber to the tube diameter was different, and this may have introduced a slightly different swirl intensity to the tube. As can be seen from Figure 9, these are in good agreement with those obtained from the flow visualization tests in Fig. 7.

Fig. 11 presents the swirl angle measured using hot wire and recirculation zone along the test tube for R= 50,000. The data of Hay et al. has been included in this result, and it can be seen that the results of the references are in reasonable agreement with the present work.

5. Conclusions

To determine some characteristics of the swirl flow induced by the swirl generator used in this investigation, the flow visualization experiments were carried out utilizing smoke as a viewing medium. The swirl angle and flow visualization tests gave the following conclusions about characteristics of the swirl flow in a circular tube. An important consideration is that the stream line angles are nearly identical to the swirl angle. The swirl flow starts with an angle of 54° to 55° with respect to the axial direction and decays to 15° ~20° at the end of the test tube. There was a vortex core or reversed flow condition near the center of the tube. It is found that the swirl angle and vortex core depended on the swirl intensity along the test tube. Lastly, the swirl angle measured using a hot wire and flow visualization reasonably agree with those of Sparrow's and Hay's .

Acknowledgments

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