Experimental Study on Swirling Flow with Sudden Expansion by Using 3D Particle Image Velocimetry Technique and Heat Transfer in a Circular Horizontal Tube

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Abstract

The effect of swirling on the flow characteristics of tubes with sudden expansion is experimentally examined by 3D particle image velocimetry(PIV) technique to determine velocity profiles. The swirling flow of water in sudden 1:2 axisymmetric expansion has been previously studied within a horizontal round tube. A tangential slot is used as a swirl generator for swirling flow, whereas a honey comb is used for flow without swirling. Three velocities with swirling flows are compared along the test section at Re=14800, and the streamline in the recirculation zone is described. In addition, heat transfer results are include and compared the Nusselt number with and without swirl flow for reattachment length.

Keywords: *swirl, recirculation, streamline, reattachment*

1. Introduction

Swirling flows in circular and rectangular tubes have received increased research attention. The characteristics of turbulent swirling flows are extensively studied because of the technological and scientific importance of these flows. Swirling flows improve heat transfer in tube flows because of the effect of the streamline curvature associated with the tangential velocity component.

Nuttall [1] performed an experimental work in a vertical circular tube using guide vanes to produce swirling flow at Re = 3×10^4. Reverse water flow occurs in the center of the pipe for specific rates of swirling and discharge. As the swirling intensity increases, the axial velocity at the center of the test tube becomes negative. However, a positive axial velocity is observed at a high swirling intensity near the tube wall.

Binnie, *et al.*, [2] conducted experimental studies on test sections with different diameters. They examined the pressure and velocity distributions inside a convergent nozzle that discharges water downward under pressure. A volute for swirling flow was used in the test section. Results show two large departures from inviscid flow because of permanganate injection into the nozzle with a hyperdermic tube inserted through pressure tapping.

In another work of Binnie [3], a Perspex tube with an internal diameter of 2 in and a wall thickness of 0.25 in was used. A volute was utilized to generate swirling flow, which was adjusted by supply valves, inside the test tube. A notable vortex collapse occurred when the pressure head was about 9 ft.

Talbot [4] made one of the first attempts in this field in 1954, when he considered the decay of a rotationally symmetric steady swirling imposed by Poiseuille flow in a circular pipe. He used a linearization technique to solve the equations of motion by considering laminar conditions only. A further attempt to analyze the effect of swirling on laminar flow in pipes was made by Sparrow, *et al.*, [5] in 1984. The studies of Talbot and Sparrow both included the effects of mass transfer, with the former adopting a boundary layer integral method and the latter using perturbation techniques.

Max, *et al.*, [6] examined the effect of swirling on the flow characteristics in a chamber with sudden axisymmetric expansion in the ratio of 2.5. Particle image velocimetry (PIV) was used to capture the instantaneous flow field with a guider vane at Re=10000, in which the swirl number was varied from 0 to 0.65. Their results showed that increasing the swirl number up to 0.65 causes the flow to reverse at the centerline because of vortex breakdown.

By contrast, swirling flow in a pipe with sudden expansion has relatively not been examined well. This field includes a wall-bounded recirculation region adjacent to the face of the expansion. Therefore, this study aims to characterize the turbulent flow that passes on a tube with axisymmetric sudden expansion and to determine the effect of the resulting swirl with 3D PIV technique and to check reattachment length using this technique and heat transfer results.

2. Experimental Rig

Figure 1 and Figure 2 are showing the experimental rig and 3D PIV system. The swirling flow of water through sudden 1:2 axisymmetric expansion was experimentally studied in a horizontal round tube. The measurements of this flow were performed with the 3D PIV system. The test section was manufactured from a round perspex tube with an inner diameter of 50 mm, a wall thickness of 5 mm, and a length of 1.2 m. A square box was installed to avoid the reflective effects of the circular tube on the results. This box recovered the reflected light waves from the visualized section of the flow.

A 3D Stereoscopic PIV technique was utilized for most isothermal flow velocity measurements. Laser (2W) was employed to measure velocities, and two charge-coupled device cameras were installed perpendicular to the visualized section of the flow.

In Figure 3, the swirl generator is indicted, which has tangential slots that consists of two cylinders with the following dimensions: an outer chamber with an outside diameter of 60 mm, a length of 150 mm, and a wall thickness of 5 mm.

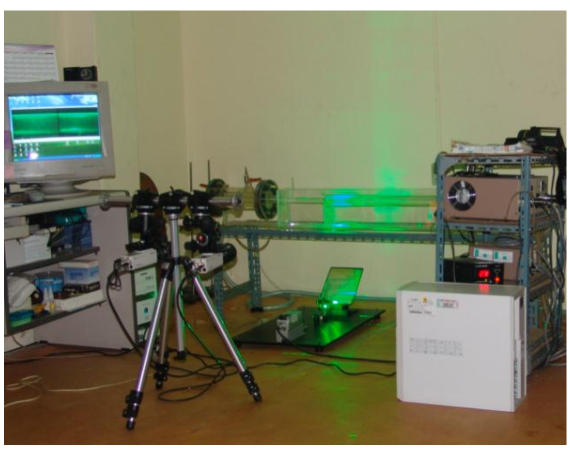

Figure 1. The Experimental Apparatus with the PIV System

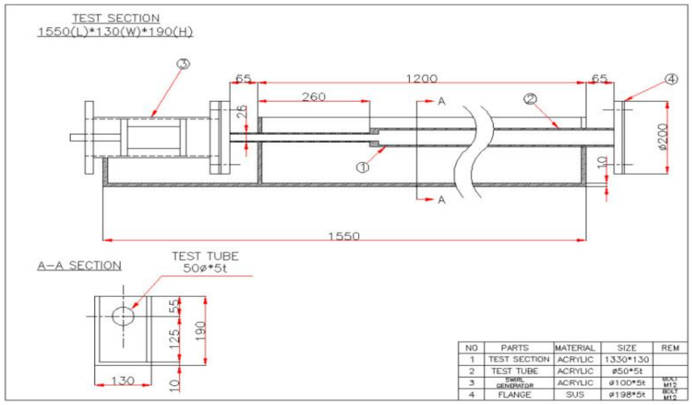

Figure 2. Schematic Diagram of the Experimental Test Tube

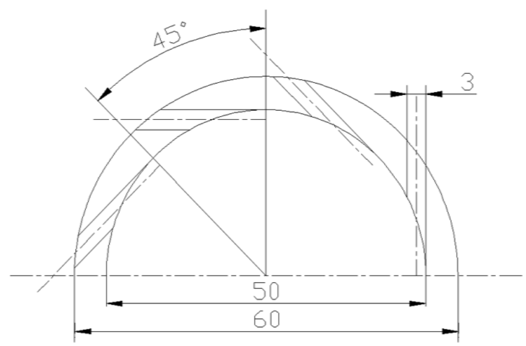

Figure 3. Schematic of the Swirl Generator

3. Results and Discussion

3.1 PIV Measurement

This study aimed to introduce different velocity profiles to the expansion region with swirling and without swirling flows. It also aimed to verify the recirculation zone of the swirling flow along the test section.

It is necessary to check the velocity profiles inside of the swirl generator, therefore Fluent 6.2 is employed to confirm it. Figure 4 is indicated the velocity vectors the entry of swirl generator and inside of it. The flow are entered through the tangential holes and then rotated along the swirl generator. The velocity vectors are reasonable to carry out this work with swirl flow in a circular tube.

Figure 5 shows the velocity vectors with swirling in a horizontal tube with sudden expansion at Re=14,800. Weak velocity vectors are found near the entry of the test tube walls. These weak vectors can be attributed to the swirling intensity that decreases as the length of the test tube increases. Therefore, the velocity vectors show positive values. However, the negative value at the entry of the test section is associated with strong swirling. Therefore, the swirl intensity is reduced at the entrance of the tube, whose diameter is 30 mm and whose length is about 100 mm. The velocity vectors are also inclined along the test section, and they increase toward the center of the test tube. This region seems to be the recirculation area. From these vectors, the mean of the velocities with swirling were calculated along the test section at Re=14,800.

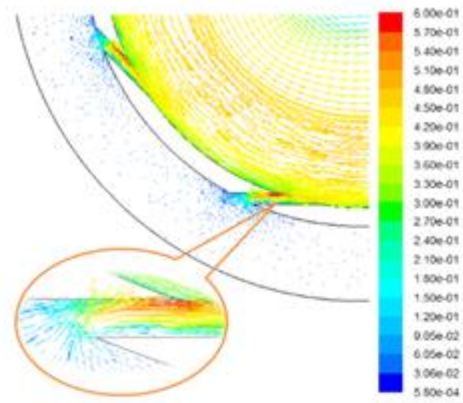

Figure 4. Velocity Vectors in the Swirl Generator

Figure 6 shows the mean velocity profiles with swirling for axial, tangential, and radial velocities at Re=14,800. Axial velocities showed higher values than tangential and radial velocities at the centerline of the test section. These results can be attributed to the weak swirling intensity at the test section. However, the axial velocities near the tube wall are nearly zero or negative in value, a finding that is related to the recirculation area.

The axial velocities are compared along the test section with swirling at Re=14,800 in Figure 7. The axial velocities show low or negative values at the entry point. However, they increase with an increase in the length of the test tube. This result is attributed to the weak swirling intensity.

Figure 8 shows the streamlines along the test section with swirling flow at Re=14,800. The figure clearly illustrates the recirculation zone and the reattachment point. The reattachment length with swirling has a value of about 80.0mm at Re=14,800. The length of the recirculation point decreases with an increase in swirling intensity and Re number.

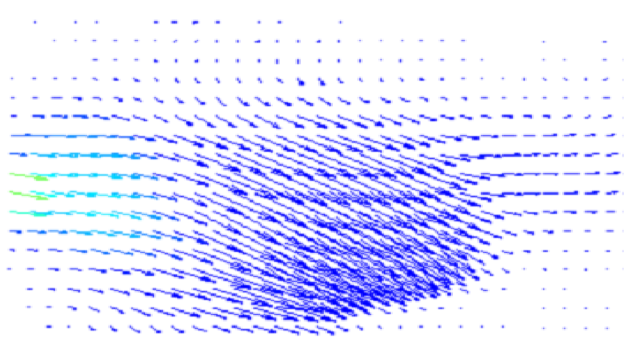

Figure 5. Velocity Vectors with Swirling at Re= 14,800

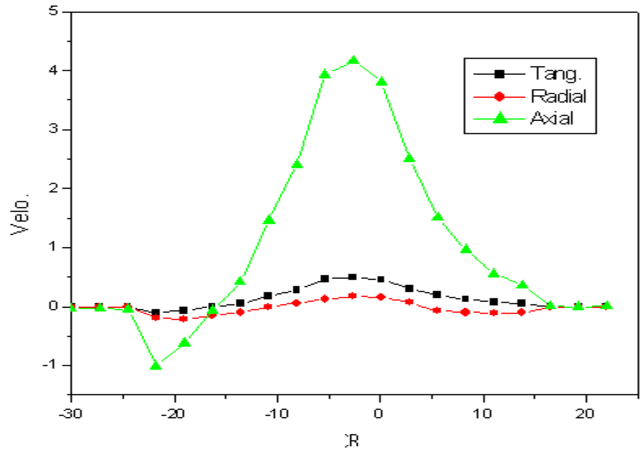

Figure 6. Mean Velocities with Swirling at Re=14,800

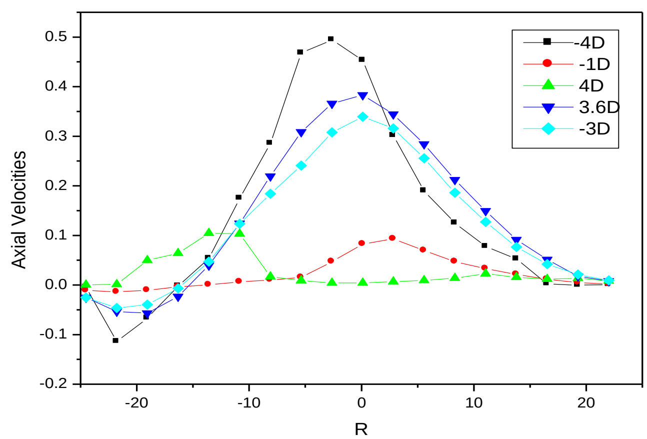

Figure 7. Axial Velocities with Swirling along the Test Tube at Re=14,800

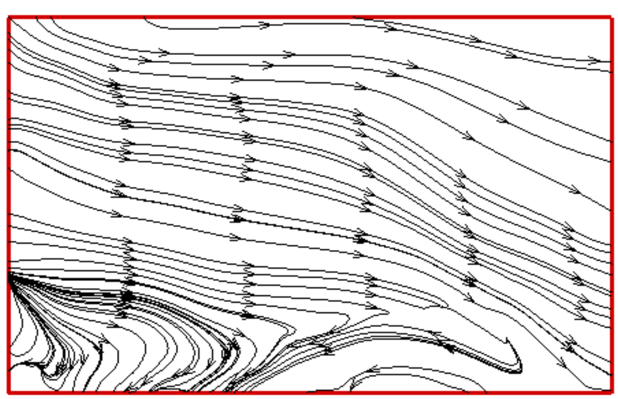

Figure 8. Streamlines with Swirling Flow at Re=14,800

3.2 Heat Transfer Measurement

A uniform heat flux (1.75kW1.75Kwx24V) is employed for heat transfer work in 50mm of a horizontal copper tube. K-type thermocouples are used to measure temperature profiles with without swirl flow and then Nusselt numbers are calculated for comparision with swirl and without swirl flow.

Figure 9 is presented the ratio of Nu/Nudb for Re=60,000~100,000. Where, Nu and Nudb are indicate Nusselt number for without swirling flow and from the Dittus-Boelter equation, respectively. The Nusselt number ratios without swirl are showing are steeply increased the entry of the test tube until the ratio is around 4.9 at x/d=5 and then suddenly decreased by the end of the test tube. In case of without swirl flow, x/d=5.0 is considered the length of recirculation region for these Reynolds numbers. Because, the velocity are zero at x/d=5.0 so the heating flux is very the highest.

Figure 10 is demonstrated of Nu/Nudb for Re=60,000 with swirl. In this figure, Nu is indicate the Nusselt number for swirling flow. The maximum value of Nu/Nudb is around 8.0 and x/d= about 2.5. Therefore, the attachment length is about 2.5d with swirling flow.

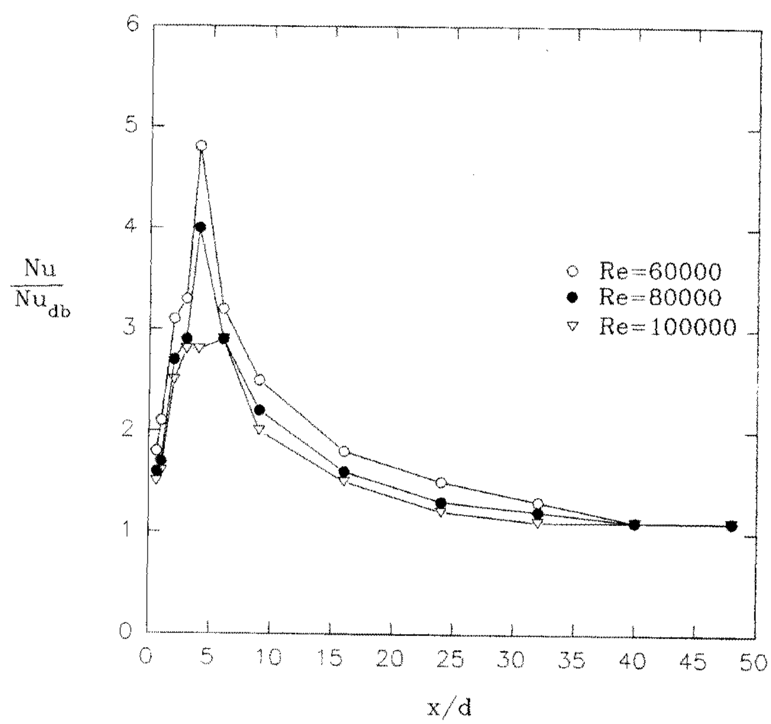

Figure 9. Distribution of Nu/Nu_{db} along the Test Tube without Swirl

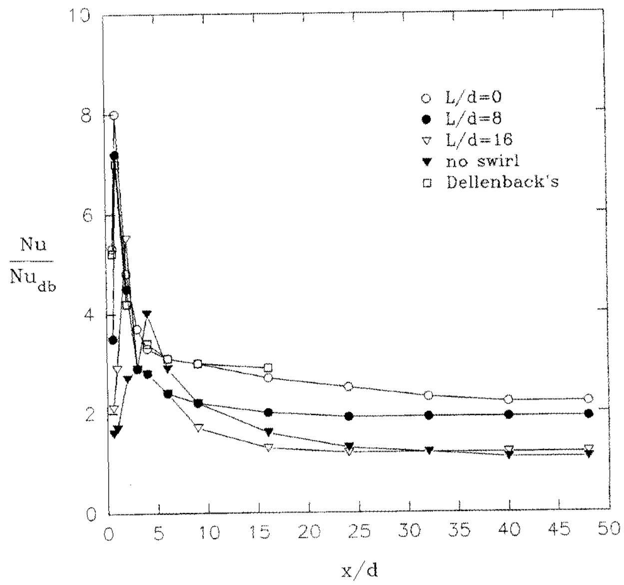

Figure 10. Distribution of Nu/Nu_{db} along the Test Tube for Re=60,000 with Swirl

4. Conclusions

1. Weak velocity vectors are found near the entrance of the test tube wall. This finding is related to the swirl intensity, which decreases as the length of the test tube increases. The velocity vectors show positive values.
2. Axial velocities have higher values at the centerline of the test section than the tangential and radial velocities. These results are attributed to the weak swirl intensity at the test section. However, the axial velocities near the tube wall are nearly zero or negative in value, a finding that is related to the recirculation area.
3. The reattachment length with swirling has a value of about 80.0mm at Re=14,800. The length of the recirculation point decreases with an increase in swirling intensity and Re number.
4. In case of without swirl flow, x/d=5.0 is considered the length of recirculation region for Re=60,000~100,000. The attachment length is about 2.5d with swirling flow.

Acknowledgements

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