MEASUREMENT OF DEVELOPING TURBULENT FLOW IN A U-BEND OF CIRCULAR CROSS-SECTION

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ABSTRACT

A full mapping of the velocity and Reynolds stress distributions of the 3-dimensional turbulent flow in a strongly 180 degree curved pipe and its tangents was obtained by hot-wire anemometer. Slanted wire is rotated into 6 orientations and the voltage outputs from them are combined to obtain the mean velocity and Reynolds stress components. It was found that the strength of the secondary flow reaches up to the 35% of bulk mean velocity. The strong counter-rotating vortex pair induced by the transverse pressure gradient and centrifugal force imbalance grows up to $\theta=67.5^\circ$ into bend. But the counter-rotating vortex pair breaks down into two cell pattern after $\theta=90^\circ$ of bend. Significant double maxima in the streamwise velocity profiles appear in the bend region due to the breakdown of counter-rotating vortex pair..

INTRODUCTION

Turbulent flows in a curved duct are widely encountered in the mechanical equipment and systems, for example, in the flow passage between turbine and compressor blade, pipe bends in heat exchangers, cooling passages inside the heating system and blood vessels.

In a curved duct, radial pressure gradients push the slowly moving fluid near the side walls toward the convex wall while the fluid near the plane of duct symmetry toward the concave wall. This viscous-inviscid mechanism creates secondary flow. Secondary flow can be of the order of 10~40 % of the mean streamwise velocity (Johnson, 1984).

For twenty years, a large amount of measurements have been conducted for the developing turbulent flows in the curved ducts of rectangular cross-section (Chang, Humphrey and Modavi, 1983). However, the measurements of turbulent flow field in the curved pipes appear to be relatively sparse, although the informations on the flow fields in the curved pipe configurations are more important in practice. It is partly due to the greater difficulties associated with the experimental method (Azzola, Humphrey, Iacovides and Launder, 1986).

Rowe(1970) obtained the total pressure and yaw results for the turbulent flow in a 180 degree bend and the attached downstream tangent. Rowe reported that the secondary flow is most intense at about 30° into bend. Near this position, the total pressure gradient induces a streamwise component of vorticity opposite in sense of rotation to the streamwise vorticity produced at the entrance of the bend. Rowe also reported that the curved pipe flow is essentially fully developed past $\theta=90^\circ$. There is evidence of local reversal in the secondary flow direction along the bend symmetry plane between $\theta=90^\circ$ and X/D=+5. But Rowe's experimental results were uncertain because of the effect of the mechanical probe used in the measurement on the flow field could not be removed. Azzola, Humphrey, Iacovides and Launder (1986) investigated the developing turbulent flow in a strongly curved 180 degree pipe and its downstream tangents by Laser-Doppler anemometer. They measured the longitudinal and circumferential velocity components and three Reynolds stress components. But they could not provide a full mapping of the primary and secondary velocity fields and Reynolds stress distributions over the entire flow regions because their measurements were restricted to vertical (radial) scan in the surface $\varphi=\pi/2$ in the symmetrical upper half of the test section.

The present measurement on the 180° curved pipe flow was aimed at providing a more complete mapping of the

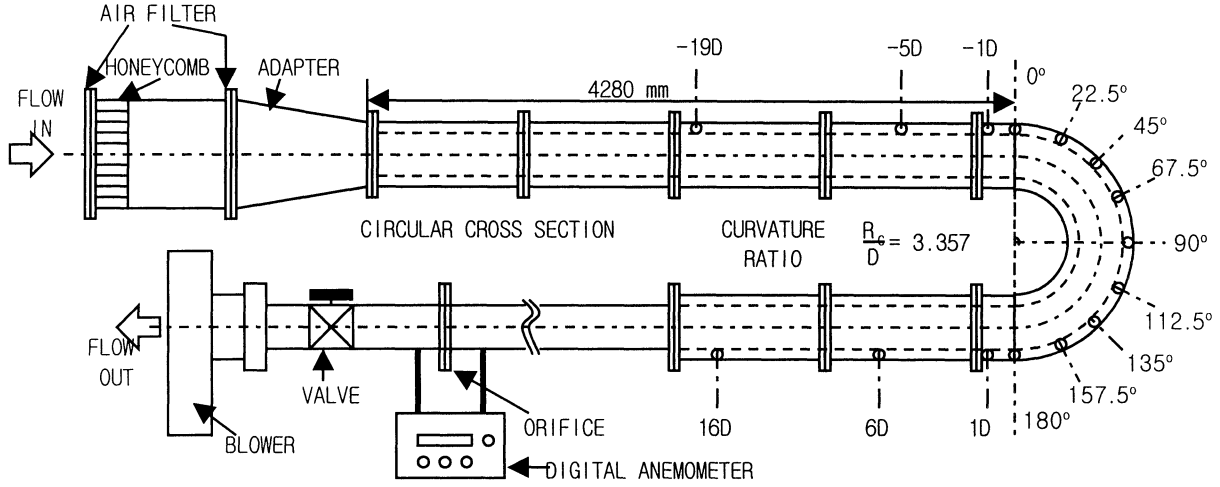


Figure1. Schematic diagram of experimental apparatus.

turbulent flow over the entire cross-sectional planes .

EXPERIMENTAL APPARATUS

The basic components of the test section are shown schematically in figure 1. They comprised two straight pipes and a 180° curved pipe, constructed from transparent plexiglass. The pipe cross-section is circular throughout with a 88.9±0.4 mm inner diameter (D), The ratio of mean curvature of the bend to hydraulic diameter (Rc/D) is 3.357. The curved pipe section is constructed by fitting together two symmetrical half sections of plexiglass, each respectively machined on one of the two flat faces to contain the shape of a semicircular open channel. This method of construction ensures that when matched at the common symmetry plane the cross-section of the resulting curved pipe was accurately circular.

Experiments were performed for Reynolds number similar to that of Azzola, et al.(1986) (Re=57,400). The Reynolds number is based on the bulk fluid velocity (W_b). The associated Dean number ($De=Re(D/Rc)^{1/2}$) is 31,300.

Measurement of the mean flow and turbulent characteristics were made using a KANOMAX 7224 series hot-wire anemometer. The hot-wire probe and probe supporter were fixed with a duralumin case which was itself firmly bolted to a x, y, z traversing and rotating mechanism. The traversing and rotating mechanism could displaced the hot-wire probe 15.0 cm in 0.1 mm increments on the probe axis by means of four linearly encoded stepping motors monitored by a personal computer.

Following the symmetry and mass flow confirmations, all subsequent measurements were conducted at X/D=-19, -5, -1, +1, +6, +16 in the straight pipes and $\theta = 0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5$ and 180 degree in the bend(figure 1).

Scans were made at the surface at $\varphi = 0, \pi / 8, \pi / 4, 3\pi / 8$ and $\pi / 2$ (figure 2). At each of these stations 21(or 11) radial positions were probed, starting at the first position fixed at 4.45 mm from the outside pipe wall ($r/(D/2) = 1$) and moving in increments of 4.0 mm toward the opposite wall ($r/(D/2) = -1$).

Figure 2 illustrates the layout of the domain of interest of the curved pipe as well as that of the coordinate system. As shown, the length of the entrance tangent is 48.2D and that of the exit tangent is 24.1D.

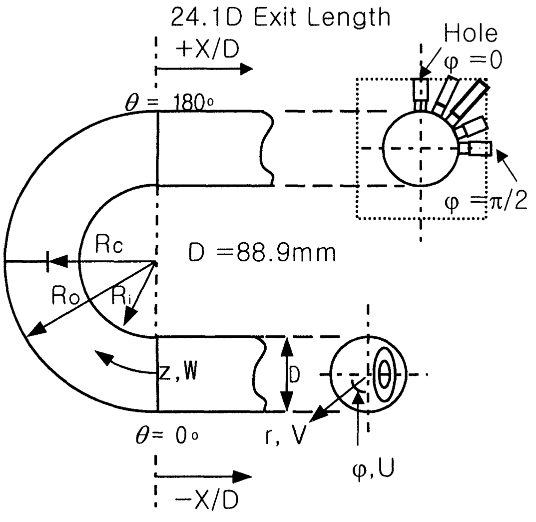


Figure 2. The test section configuration and definition.

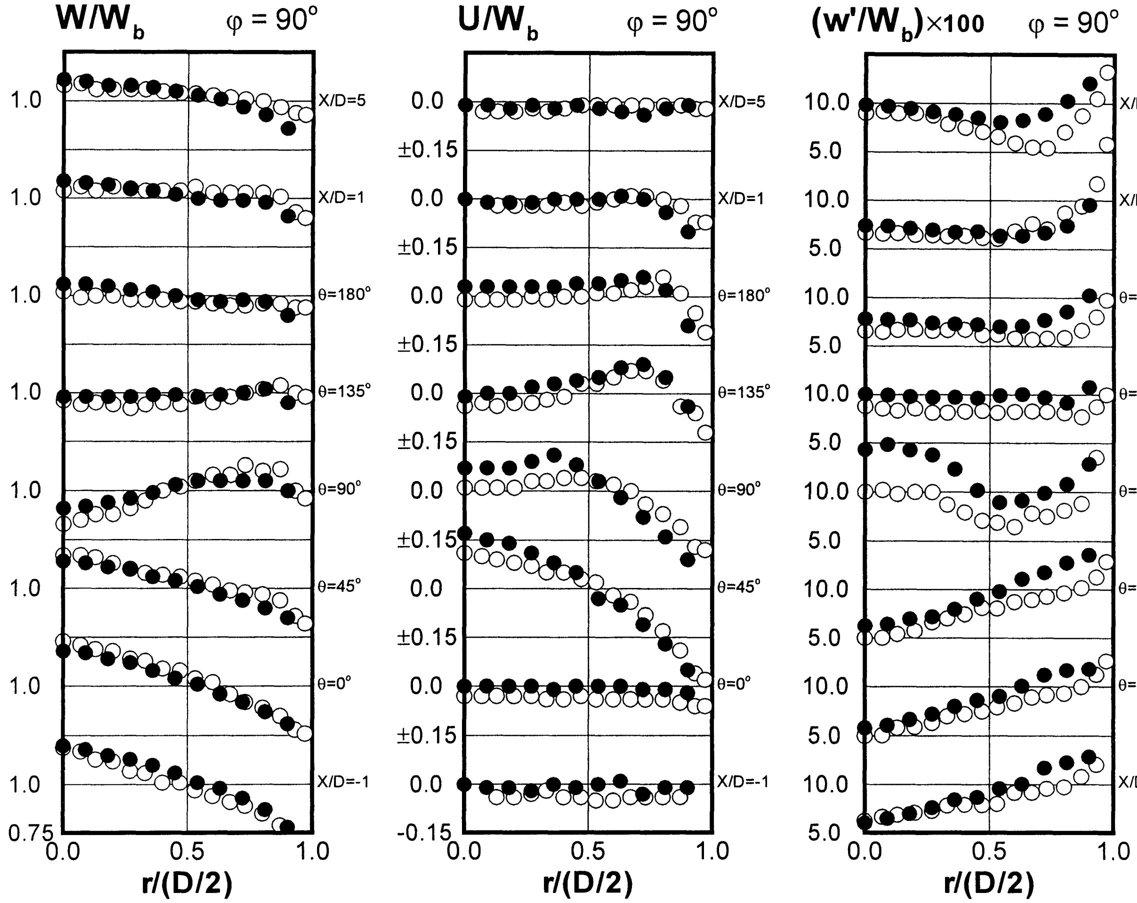


Figure 3 Comparisons of measured results for the longitudinal(W) and circumferential(U) mean velocity and longitudinal turbulence intensity components at substantial longitudinal stations in a 180° curve pipe with straight tangents. ● : present data, ○ : Azzola et. al(1986)

THEORETICAL ANALYSIS

The main principle of hot-wire anemometry was proposed by King (1914). Afterwards many researchers have developed methods of determination of the mean velocity vector and Reynolds stress tensor in the direction of the axes of the spatial coordinate system for three dimensional flows (Champagne, Sleicher and Wehrmann, 1967).

The linearised relationship of the hot-wire anemometer is obtained by means of a calibration. The overall characteristics (transfer function) of the anemometer was made to have the form :

$$E = S \cdot E_{eff} \tag{1}$$

where E stands for the instantaneous output of electrical signal and E_{eff} for the so-called effective cooling velocity. S is the slope of the linear calibration curve.

Jorgensen(1971) proposed the following expression for the effective velocity :

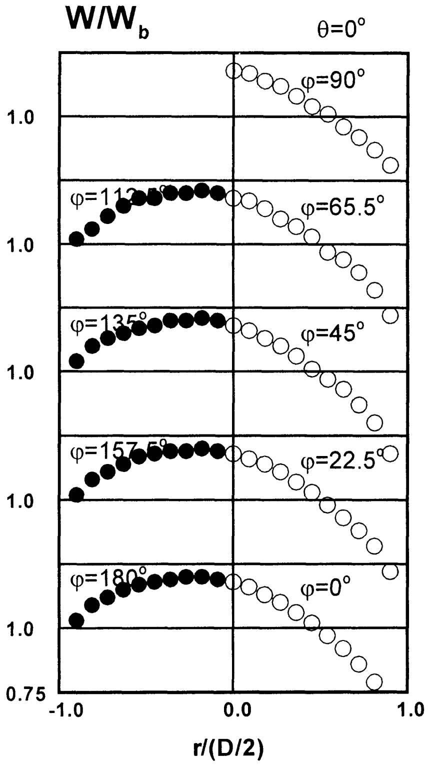
$$U_{eff} = (U_N^2 + k^2 U_T^2 + h^2 U_B^2)^{1/2} \tag{2}$$

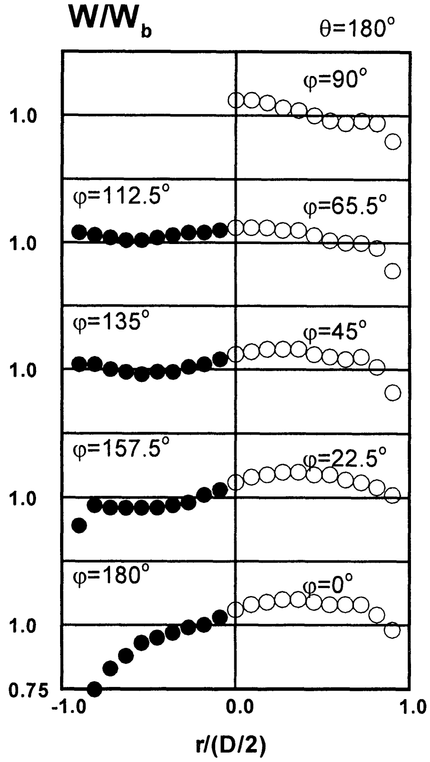
where U_N, U_T and U_B stand for the velocity perpendicular, parallel and binormal to hot-wire respectively. k is the sensitivity coefficient of the component parallel to the wire axis. The sensitivity coefficient h describes the unsteadiness of the heat transfer at the periphery of the hot-wire due to different flow conditions.

In this experiment, the method of direct determination of the mean velocities developed by Acrivlellis(1977) was employed. And the modified form of the expression proposed by Dvorak and Syred(1972) was used for the calculation of the Reynolds stresses.

RESULTS AND DISCUSSIONS

Figure 3 shows the comparison of the longitudinal





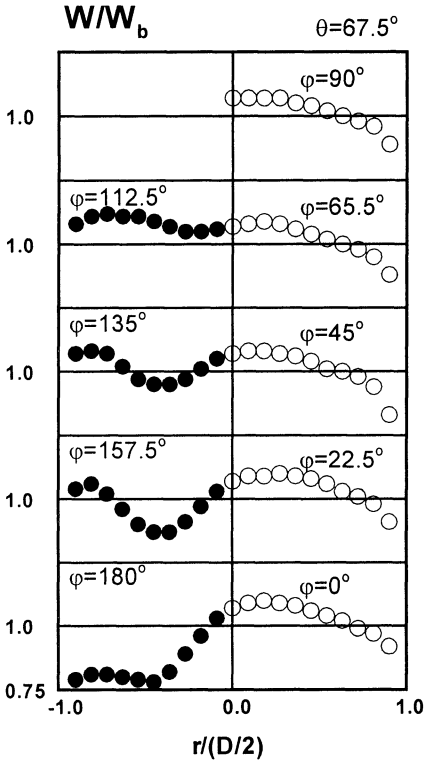


Figure 4. Distribution of the longitudinal mean velocity

(W/W_b) and circumferential (U/W_b) velocity components and the circumferential turbulent intensity (u'/W_b) measured by Azzola, et al. with the present measurement at $\varphi = 90°$ in the symmetrical upper half of the test section. As shown in figure 3, two longitudinal mean velocity distributions along the line $\varphi = 90°$ give very good agreement. The two circumferential turbulent intensities are also very close except $\theta = 90°$ at which there is a discernible difference between the two turbulence intensities.

Figure 4 shows the variation of the longitudinal velocity in the sequential cross-sectional planes from the inlet to the outlet of the bend. At the bend entrance ($\theta = 0°$), W velocity profile of present measurement shows different shapes with that of the fully developed velocity measured by Laufer (1954) in a straight pipe. Present measurement does not show symmetry in W velocity profile at $\theta = 0°$. From the inlet of the straight pipe to the entrance of the bend, the flow is gradually accelerated in the inner wall region ($r/(D/2) < 0$) and decelerated in the outer wall region ($r/(D/2) > 0$) of the bend. At $\theta = 67.5°$, the W velocity profiles show some acceleration near the wall while some loss of velocity in the vicinity of $-0.5 < r/(D/2) < 0$. The most interesting feature of this 180° curved pipe flow is that the W velocity profiles along the radial line show double peaks due to the break down of counter-rotating vortex pair of secondary flow into two cell pattern. At θ = 180°, W velocity profiles in the vicinity of inner wall is lower than that of outer wall. This trend is maintained throughout the whole bend region.

A more complete picture of the development of secondary flow through the bend is provided in figure 5. A strong cross-stream motion induced by the transverse pressure gradient and centrifugal force imbalance grows up to θ = 67.5° forming a counter-rotating vortex pair.

At θ = 67.5°, the secondary flow intensity near the wall increases up to $((U^2+V^2)^{1/2}/W_b)_{max} \sim -0.28$. However, in the last half of the bend(θ = 90° to 180°), the secondary flow is gradually diminished and divided into some weak vortices. The intensity of secondary flow of a 180° bend of a circular cross-section is lower than that of the corresponding 180° curved duct of a square cross-section.

Figure 6 shows the distributions of Reynolds stresses at the cross-sectional plane of θ = 67.5°. At this plane, the variation and magnitude of Reynolds stresses are higher than that of the straight pipe. Because of the additional mean strain associated with the distortion of the streamwise velocity profiles, the level of Reynolds stress substantially rises. Reynolds stresses are rapidly generated near the inner wall of symmetry plane of entrance region of the bend and then the higher stress region gradually propagates toward the core of the bend. But it does not propagate over $r/(D/2) > 0$. Centrifugal force associated with the curvature of the bend affects directly both the mean motions and turbulent structures. The action on the mean motions induce the secondary flow while the effects on the turbulence structures modify the mixing processes. Since the mean flow field alters the turbulent structures and the variation of the turbulence structures also affect the mean flow field. Thus the two effects become inextricably entwined.

CONCLUSIONS

In this paper a complete mapping of turbulent flow characteristics in a U-bend of circular cross-section is reported for the conditions corresponding to those for which Azzola et al. provided detailed data. The following conclusions are obtained

(1) The present measurements and the results by Azzola, et al. show very good agreement except θ = 90° in which the secondary flow pattern is rapidly changing.

(2) The W velocity profiles along the radial lines give double peaks due to the breakdown of secondary flow field into two cell pattern after θ = 67.5°.

(3) The level of the measured secondary flow intensity in the present measurement is lower than that of the 180° curved duct of a square cross-section.

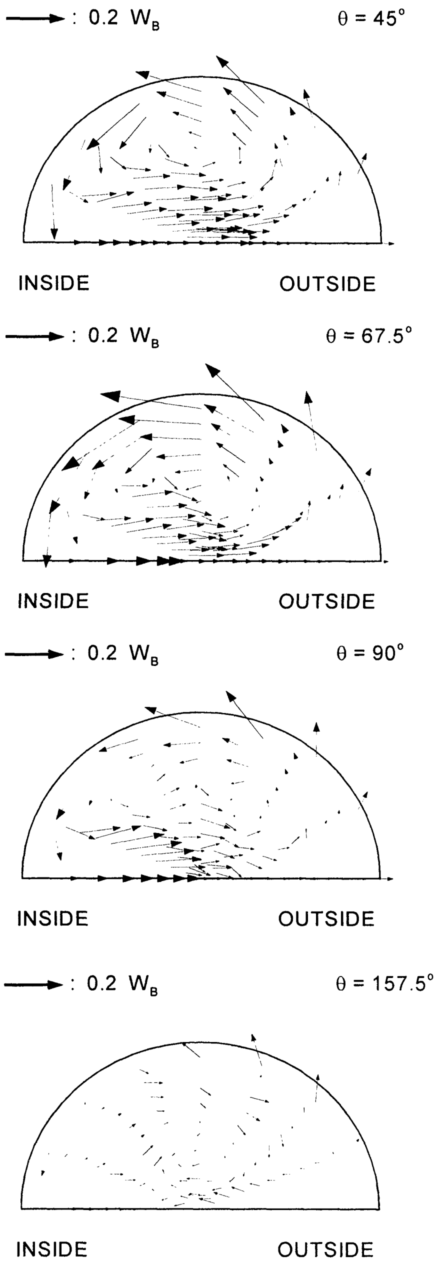


Figure 5. Cross-stream velocity vectors.

(4) Reynolds stresses are rapidly generated near the inner wall of symmetry plane in the first half of the bend, hereafter the higher stress region gradually propagates toward the core of the bend.

(5) The present study provides a complete mapping for the distributions of the primary and secondary velocities and turbulent intensities over the 180° curved pipe and its tangents. This results would help workers who want to develop the more reliable turbulent models for the CFD analysis of three dimensional turbulent flows.

ACKNOWLEDGEMENTS

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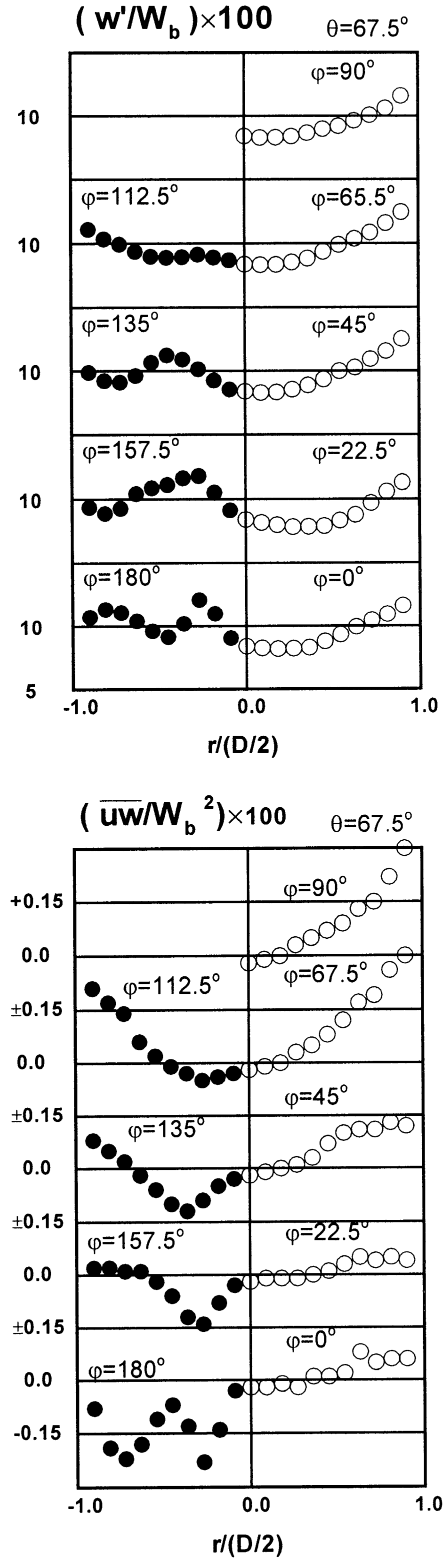

Figure 6 Distribution of Reynolds stresses.