LDV Measurements of Velocity Distribution in Unsteady Bend Flow

M. Sumida, T. Senoo, and J. Yamamoto

***Abstract*—**The distributions of velocity in an unsteady turbulent flow through a bend were investigated experimentally. The bend had a curvature radius ratio of 4.0, into which a pulsating flow with a moderate frequency was provided. The velocity was obtained by laser Doppler velocimetry at several axial stations. The phase-averaged velocity fields of the primary and secondary flows are illustrated and examined. Simultaneously, we discuss the transition of phenomena in the axial direction and with time.

***Keywords*—**Bend, LDV Measurement, Turbulent Flow, Unsteady Flow, Velocity Distribution.

I. Introduction

FLOWS in both bends and curved pipes have been examined for a wide range of industrial uses, such as heat exchangers and elements in various piping systems, by many researchers in fluid mechanics. Most of the studies have mainly concerned with steady flows. On the other hand, the research on unsteady flows started in the 1970s and has progressed rapidly [1]. However, researchers have focused on laminar flows with relatively low Reynolds numbers.

From an industrial viewpoint, turbulent unsteady flows are very important. However, there have been few works on such flows [2]–[5]. Moreover, as for the turn angle of bends and elbows, there are a lot of cases of 90° [2], [5]. However, no measurements have been reported for a fully developed pulsating turbulent flow entering the 90° bend of a pipe with a circular cross section, despite the many practical uses. Therefore, the understanding the flow behavior in 90° bends is insufficient.

In this study, we consider the problem of a pulsating turbulent flow through a 90° bend with $R_c = 4$. Measurements were made for the axial and secondary flow velocities by laser Doppler velocimetry (LDV). Furthermore, we discuss the periodic changes in their phase-averaged distributions along the bend axis.

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II. Experimental Apparatus and Measurement Method

A schematic diagram of the experimental apparatus together with the coordinate system is shown in Fig. 1. The working fluid was water. The inside diameter of the test bend was d (= $2a$)= 22.0 mm and the curvature radius was $R = 44$ mm, giving a curvature radius ratio R_c (= R/a) of 4. The volume-cycle pulsating flow was generated by superimposing an oscillating flow driven by a piston on a steady flow supplied by a pump. Thus, the instantaneous cross-sectional average velocity W_a can be expressed in the form

$$W_a = W_{a,ta} + W_{a,os} \sin\Theta. \tag{1}$$

Here, Θ (=ωt) is the phase angle, with ω and t being the angular frequency and time, respectively. Moreover, the subscripts *ta* and *os* indicate time-mean and amplitude values, respectively.

The instantaneous velocities, w and u, in the axial and outward directions, respectively, were obtained by a laser Doppler velocimeter. The LDV data at each measuring point were taken for 200 to 300 pulsation cycles and the phase-averaged velocities, W and U, were obtained.

The experiments were performed under the conditions of α = 20, Re_{ta} = 20000 and η = 0.5 [2], [3], [5]. Here, the Womersley number is defined as $\alpha = a\,(\omega/\nu)^{1/2}$, with ν being the kinematic viscosity of the fluid. The mean Reynolds number is expressed as $Re_{ta} = W_{a,ta}\, d/\nu$ and the flow rate ratio is given by $\eta = W_{a,os}/W_{a,ta}$.

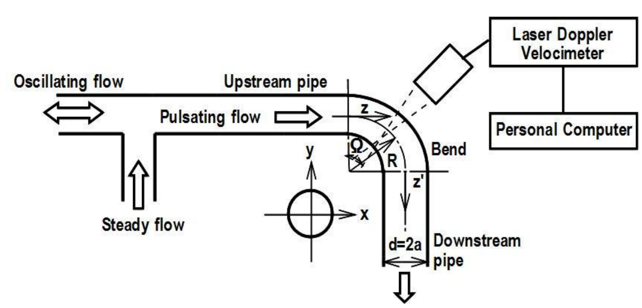
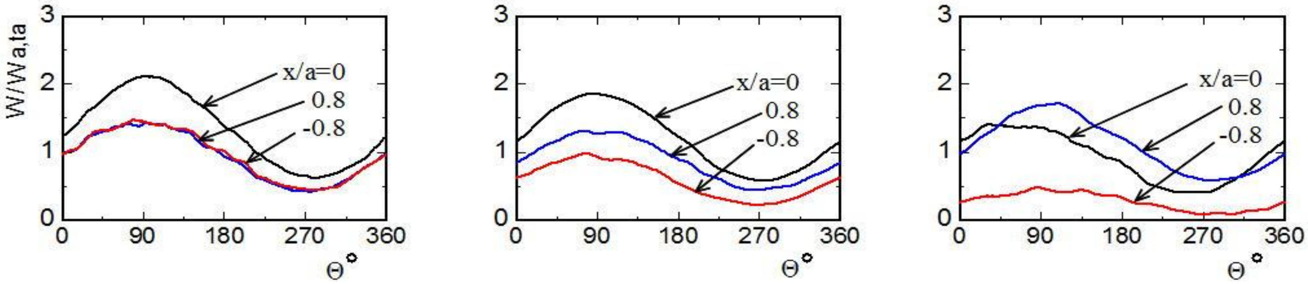


Fig. 1 Schematic diagram of experimental apparatus and coordinate system



(a) z/d =-0.2 (b) Ω = 60° (c) Ω = 90°

Fig. 2 Changes in phase-averaged velocity W with time

III. Results and Discussion

Figure 2 shows waveforms of W at the radial positions of x/a = 0 and ±0.8. The axial velocity W changes almost sinusoidally with time. However, the amplitude of W on the pipe axis is reduced in the bend. In the bend, the amplitude of W becomes large near the outer wall. In contrast, near the inner wall, it is reduced, and W at Ω = 90° also changes with a phase lag. Thus, unsteadiness is exhibited in the flow in a complicated manner.

Figures 3 and 4 show the distributions of the W and U on the x-axis, respectively. In the upstream straight pipe (z/d = –2), the W at each phase shows an axisymmetric profile similar to that of the steady flow. Near the bend entrance (z/d = –1), fluid with higher axial velocity begins to move toward the inner wall for Θ = 0–90°. Behind the bend entrance, Ω=0–30°, the accelera -tion of the fluid becomes largest the most in the inner region of the bend. Consequently, the position of the maximum axial velocity is biased towards the inner wall when the flow rate is large. At this time (Θ = 90°), the secondary flow motion at Ω = 0° has a negative velocity. On the other hand, the fluid with a higher speed in the central region of the cross section is subjected to a strong centrifugal force. This forces the direction of the secondary motion to change towards the outer wall (Ω = 15°). Consequently, the U at Ω = 30° becomes approximately 50% higher than that in the steady flow at $W_{a,ta}$. Further downstream (Ω = 60°), the region with a higher speed begins to shift toward the outer wall. As a result, the axial velocity near

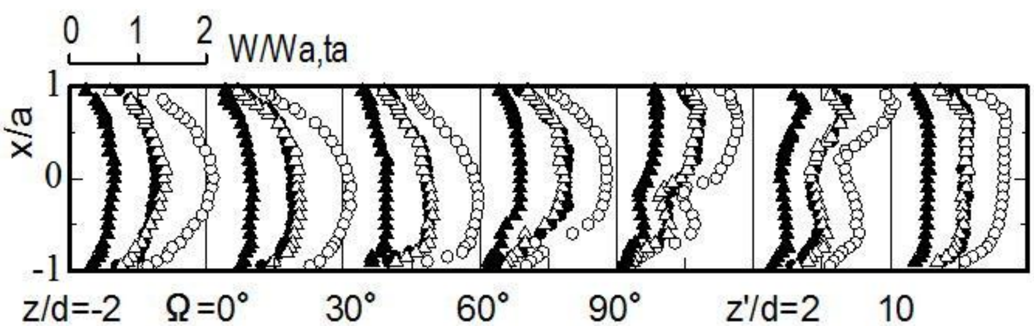


Fig. 3 Distributions of axial-flow velocity W on the x-axis
●: Θ=0°, ○: Θ=90°, △: Θ=180°, ▲: Θ=270°

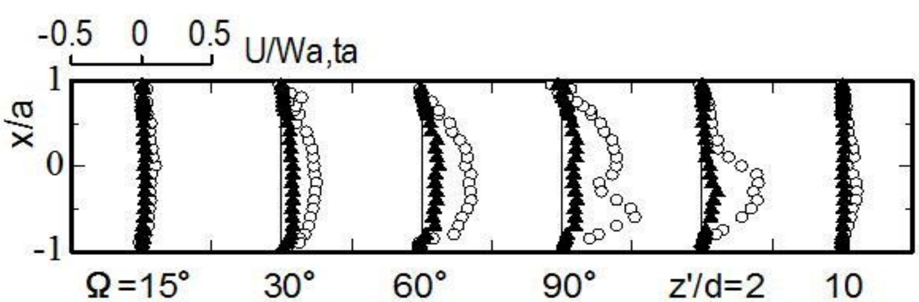


Fig. 4 Distributions of secondary-flow velocity U on the x-axis
○: Θ=90°, ▲: Θ=270°

At the bend exit (Ω=90°), fluid with a higher speed flows into the inner wall decreases rapidly.

At the bend exit (Ω = 90°), fluid with a higher speed flows into the inner wall region along the upper and lower walls. The fluid in the central part of the cross section, in contrast, is swept toward the outer wall by the strong secondary flow. Accordingly, the W on the x-axis has a distribution with two maxima, while its distribution on the y-axis has a depression in the central part. On the other hand, the secondary flow velocity is high for Θ = 60–180°. During the phases, the U profile changes into a shape with two maxima, similarly to the distribution of W.

Downstream from the bend exit, no centrifugal force acts on the fluid. Nevertheless, the U significantly increases to as high as 50% of $W_{a,ta}$ (z'/d = 0–2). Therefore, the depression in the W distribution becomes notable at z'/d =1. Further downstream, however, the W distribution at z'/d =10 has not yet recovered to that observed in the upstream straight pipe.

IV. Conclusions

The findings of this study are summarized as follows:

(1) The flow exhibits very complicated characteristics significantly different from those of a steady flow, and the velocity distribution changes in a complex manner with the phase Θ and also in the streamwise direction Ω and z'.

(2) The axial velocity W near the bend entrance has a higher distribution near the inner wall when the flow rate is large, while W near the bend exit has a depression in its distribution.

(3) The secondary flow is strongest near the bend exit and then gradually attenuates. Nevertheless, it does not disappear even at z'/d =10.

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