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A study of the flow characteristics of developing turbulent pulsating flows in a curved duct

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Abstract

Flow characteristics of turbulent pulsating flows in a square-sectional curved duct were experimentally investigated. Experimental studies for air flow were conducted to measure axial velocity profiles, secondary flow and pressure distributions in a square-sectional 180° curved duct by using an LDV system with a data acquisition and processing system which includes a Rotating Machinery Resolve (RMR) and PHASE software. Measurements were made at the seven cross-sections from the inlet (ϕ=0°) to the outlet (ϕ=180°) of the duct with 30° intervals. Pressure was measured by using a magnetic differential pressure gage. The experiment was conducted in nineteen sections from the inlet to the outlet of the duct at 10° intervals.

Velocity profiles for turbulent pulsating flows were large at the outer wall for a bend angle of ϕ=30° because of the centrifugal force. The velocity profiles were similar to those of turbulent steady flows. The secondary flow of the turbulent pulsating flow had a positive value at a bend angle of 150° without regarding the phase. The dimensionless value of the secondary flow became gradually weak and approached to zero in the region of a bend angle of 180° regardless of the ratio of velocity amplitude. The pressure difference of turbulent pulsating flows was the largest near the region of a bend of angle of 90° in the case of the middle region and became small beyond 90.

Keywords: Turbulent pulsating flow; Curved duct; Axial velocity profiles; Secondary flow; Pressure distribution

1. Introduction

The fluid flow in a 180° curved duct is more complicated than that in a straight duct [1,2]. Studies of turbulent flows in curved ducts have focused on both scientific interest and practicality in various industrial fields [3,4]. In recent years, studies have also been made on flow in human blood vessel systems and the heart [5]. In particular, effects of secondary flows on the expanding part of lung and airways have been investigated as related to the transfer of oxygen and carbon dioxide in the field of biomedical engineering [6]. In the design and operation of an air-conditioning duct system and a pipe network, both the stability and the efficiency of the entire plant are important. And, the turbulent pulsating flow is a great help to advance not only most suitable design of the exhaust pipelines, but capability and efficiency of the reciprocate engine [7]. At the end of the nineteenth century, the flows in curved tubes were introduced to the field of fluid engineering, but in the 1920's, theoretical and analytical research was mainly conducted for cases of small-curvature radius. Special fields of engineering such as physiology and bio-medical engineering have also become popular [8]. Researchers began to study pulsating flows with the development of both analytical and experimental methods, especially for the unsteady flows, which are a very complicated phenomenon. The study of unsteady flows in the curved ducts was mainly undertaken after 1970.

Lyne [9] used a pressure gradient described by $-\partial p / \partial z = \rho\omega \cdot \omega_0 \cdot \cos \omega t$ and found that the secondary flow moved from the outer wall to the inner

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wall in a circular curved duct with a large curvature radius; this type of flow is known as Lyne's type secondary flow. Singh [10] found that the axial velocity component had a negative value at velocity amplitude (A_1)=0.8 because of the effects of the bend and wall shear stress. Naruse et al. [11] measured the characteristics of blood flow in a duct of large bend such as the carotid artery by using an LDV. Sudou et al. [12] measured the velocity distribution along the axial direction for a range of curvature ratio (Rc)=1/9~1/33, dimensionless angular frequency (ω^+)=2~28, Dean number (De)=0~300, and velocity amplitude ratio(A_1) = 0.5 and 1, by using an LDV. It's very important [fso1]that the curvature ratio in curved duct has an effect on flow. Because of maximum velocity of fluid is affected by centrifugal force. In this study, the curvature ratio was fixed 1/20. The kinematic energy of the secondary flow increases in the field of a comparatively large Dean number.

In the present study, the characteristics of a turbulent pulsating flow were examined closely by an experimental analysis in a square-sectional 180° curved duct for different Dean numbers (De), dimensionless angular frequencies (ω^+), and velocity amplitude ratios (A_1).

2. Experiment

2.1 Experimental apparatus

The present experiment was performed for measurement of the velocity distribution along the axial direction secondary flow and pressure distribution for turbulent pulsating flows in the entrance region of a square cross-section 180° curved duct. Air was used as the working fluid, and an air-produced mosquito-coil smoke was used for flow visualization. A schematic diagram of the experimental apparatus is shown in Fig. 1 and the coordinate system is shown in Fig. 2. The experiment apparatus consisted of the 180° curved duct, a suction type blower to produce steady flows, a scotch-yoke type oscillator to produce unsteady flows, and a variable speed motor. In addition, a three-dimensional traverse system was incorporated for an LDV system. A constant pressure hole(93-1 drill) is punched to measure the pressure by using the high sensitivity pressure transducer. We also made punched a constant pressure hole at equal intervals of 10.

A side pressure hole is punched to establish a pressure difference converter because of the considerable pressure difference between inner wall and outer wall in the curved section.

A signal processor was used for executing the input signal from the LDV to a personal computer. PHASE (TSI.,CO) software program was used for velocity estimation of pulsating flows. A square cross-sectional 180° curved duct with a width and height of 40 × 40 [mm] was used for the present experiments. The curved section of curved duct had the same scale in height and width to the straight duct section and had a curvature radius of 400 [mm], constituting a U shape where pressure holes ware made every 10°. A side pressure hole was also installed to monitor the pressure difference due to the considerable pressure difference between the inner and outer walls of the curved section. In the velocity measurement, the scattered light obtained from flowing particles in the measuring part of duct changed the photo signal to an

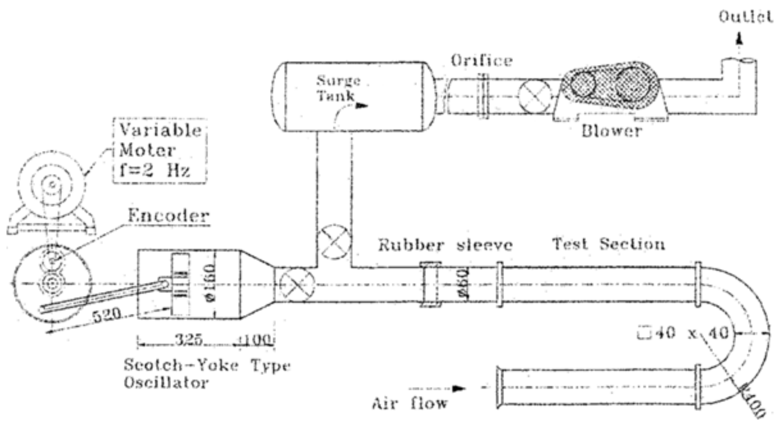


Fig. 1. Schematic diagram of experimental apparatus.

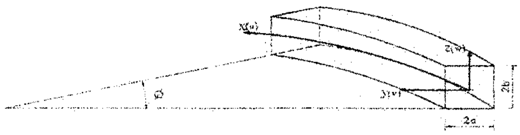


Fig. 2. Coordinate system and velocity component in a curved duct.

electric signal through a photo-electric converter which passed through a frequency shifter. The shifter maximized the signal of the phase angle, which was produced by the encoder of the driving shaft of the Scotch-yoke type oscillator, while the PHASE program handled the data acquisition of pulsating. The location of the flow, bent angle, Dean number, y/a, z/b etc. were recorded in the computer, and consequently, plotted by the ORIGIN(microcal software) graphic program. Thus, it was possible to distinguish flow direction. The pedestal signal was eliminated by the frequency shifter, and this signal inputted a signal processor and finally it appeared on the oscilloscope.

2.2 Experimental methods

The steady flows were produced in the test duct by a blower, and the oscillatory flows were produced by the Scotch-yoke type oscillator. For the oscillatory flows, the piston amplitude (A_p) was adjusted by the piston control of a crank plate attached to the Scotch-yoke type oscillator. A working fluid was generated from smoke of a mosquito-coil inhaled by the blower to the test duct. According to maker the size of the smoke of mosquito-coil particles was 0.1-0.3 μm in diameter. For an experiment with LDV, the time averaged Dean number (De_{ta}) was varied between 3350 and 7380 at an angular frequency (f) of 2.0 Hz, a piston amplitude (A_p) of 50mm and a Dean number of oscillation of 4470, the ratio of velocity amplitude (A_1) was 1.3 and 0.6, respectively.

An experimental condition is for comparison to the result by Sumida [13] and is for comparison of the flow characteristics in the straight duct. To investigate the flow development in terms of characteristics of a turbulent pulsating flow, the velocities in a curved duct were measured each 30° at a dimensionless angular frequency (ω^+) of 18.5. The moment velocities of the turbulent pulsating flow were measured at seven intervals from the duct center in the z/b-direction. The velocity distribution in the y/a-direction would exhibit greater change in the curved duct, so the measuring intervals were divided into 15 points from the duct center to both sides of the duct wall. The time-averaged Reynolds number of turbulent pulsating flow is calculated by the equation

$$Re_{ta} = \frac{u_{m,ta} \cdot D_h}{\nu} \tag{1}$$

and we fixed Re_{ta} at 3350 and 7380. The dimensionless angular frequency (ω+) and the velocity amplitude ratio were obtained from equations

$$\omega^+ = \frac{D_h}{2}\sqrt{\frac{\omega}{\nu}} \tag{2}$$

and $A_1 = |\overline{u}_{m.os.1}| / \overline{u}_{m,ta}$, respectively.

3 Results and discussion

3.1 Axial velocity distribution

The characteristics of the pulsating flow are mainly governed by the time-averaged Dean number and the ratio of velocity amplitude. Fig. 3 shows the axial velocity distributions at the dimensionless angular frequency (ω^+) of 18.5, the De_{ta} of 3350, and the ratio of velocity amplitude of 1.3. Most of the turbulent pulsating flow is similar to the developing process of a steady flow. The flow inside the curved duct produces large velocity profiles like the steady flow; the velocity profile moves from the center duct to the outer wall. A flow at the dimensionless angular frequency(ω^+) of 18.5 shows a very complex development because of the effect of the unsteady property of the flow due to the increase of ω^+. The axial velocity distribution manifests a concave type in the center of the duct because of the large phase difference among velocities. During the phase angle($\omega t/\pi/6$)≒9~0, the fluid at the inner wall is accelerated by a strong positive pressure gradient and the flow is reversed rapidly so that it can proceed in the positive direction.

In a flow of velocity amplitude (A_1)=1.3, the axial velocity distribution looks nearly symmetric at a bend angle of 0° The velocity difference between the inner and outer wall is large at bend angles of 30° and 90° because the greatest velocity is created by the centrifugal force against the outer wall.

Although the average velocity is a positive value, it flows backward from the inner wall in the phase angle ($\omega t/\pi/6$)=9. At a bend angle of 60°, we think the velocity energies of the main flow and secondary flow are nearly parallel, and the amplitude appears small form as balancing each other of velocity in the main flow owing to the secondary flow. The flow is gradually stabilized at a bend angle of 150°. Fig.4 shows the axial velocity distributions at the dimensionless angular frequency of 18.5, the De_{ta} at 7380 and the ratio of velocity amplitude (A_1) at 0.6. The axial velocity distribution of the turbulent pulsating flow is similar to that of the steady flow because of the steady property of the flow. As the Dean number becomes larger, a concave phenomenon of axial velocity distribution in the duct center occurs in two positions at the inner and outer walls.

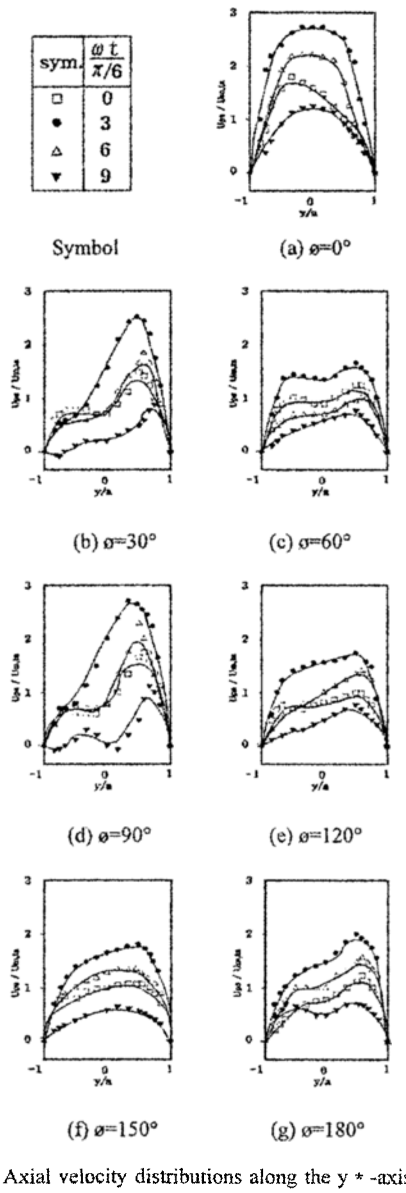


Fig. 3. Axial velocity distributions along the y * -axis in the curved duct for the turbulent pulsating flow at the De_{ta}=3350, ω^+ =18.5, A_1=1.3.

However, the axial velocity distribution becomes flat by the moving forward of the phase and the acceleration of the fluid in the duct center. On this account, the additional vortex disappears. Provided the time-averaged Dean number is increased, the convex part of the duct center becomes a distributed form close to symmetry.

When comparing Fig. 3 and Fig. 4, the time-averaged Dean number gets higher and the ratio of velocity amplitude(A_1) gets lower as the time-averaged Dean number(De_{ta}) increases. With this, we can observe that the velocity gradient of the inner wall and outer wall in a curved duct is comparatively slow and the velocity transformation gets smaller. Therefore, the velocity gradients at the inner and outer walls of the curved duct were relatively small, and the velocity changed by a small amount. When the bend angle exceeded 30° in the total phase, the axial velocity distribution became large and slow moving at the outer wall because of the same amount of centrifugal force during the period of revolution due to the development of flow at this point. The distribution of an annular type flow was seen near a bend angle of 90°. In addition, the configuration of a track line from Fig. 3 to Fig. 6 shows the velocity distribution of the particle route and it was plotted by the ORIGIN software.

3.2 Secondary flow distribution

As the bend angle of the curved duct increases, secondary flow is generated because the maximum velocity moves to the outer wall by means of the inertia force and centrifugal force on the fluid. In the case of real fluids, the fluid velocity near the wall was slowed down by the effect of viscosity.

In the curved duct, the fluid at the duct wall is generated the secondary flow by flowing toward the direction of low pressure because the fluid particles are not parallel to the pressure field relative to the centrifugal force.

Many vortices are generated from one vortex in the section with low dimensionless angular frequency (ω^+). These vortices repeat the generation and extinction, union and disunion during a period of revolution. The distributions of secondary flow show a relatively complex phenomenon in the entrance region of the curved duct.

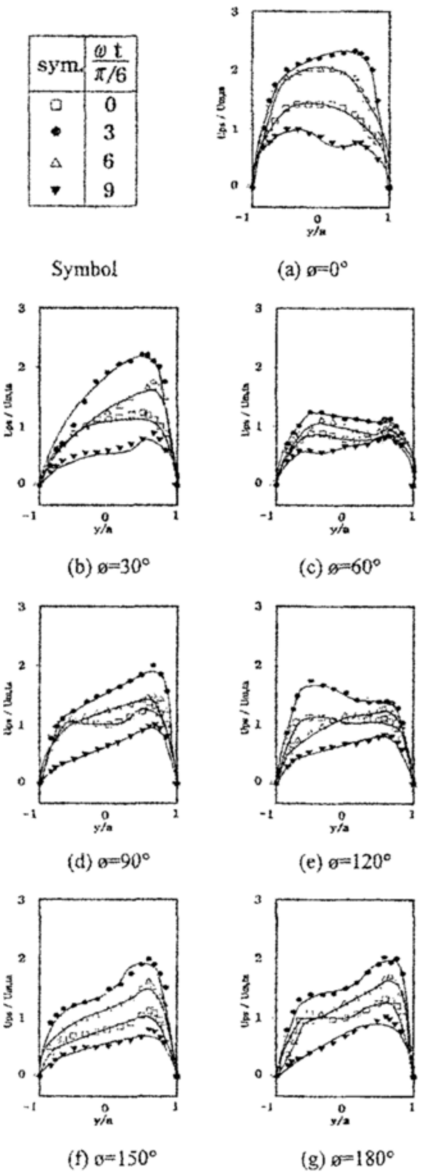


Fig. 4. Axial velocity distributions along the y * -axis in the curved duct for the turbulent pulsating flow at the De_{ta}=7380, ω^+=18.5, A_1=0.6.

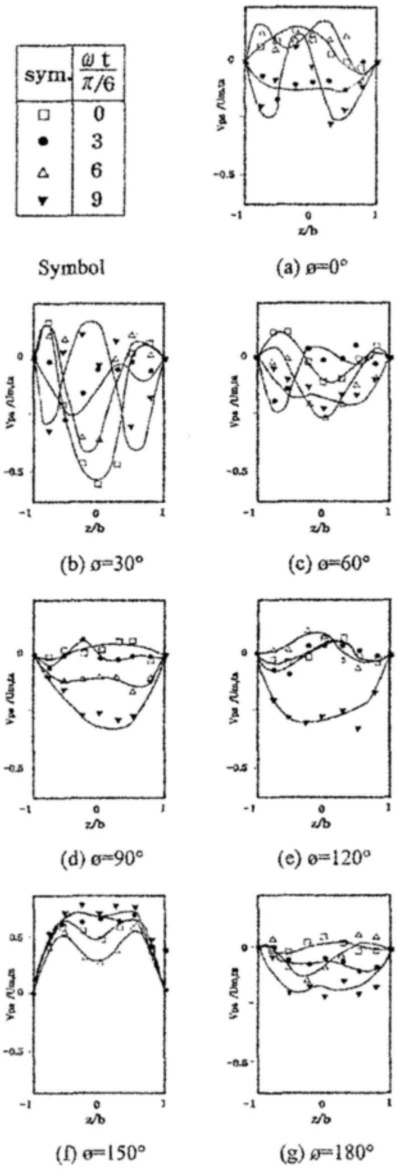


Fig. 5. Secondary flow distributions along the z * -axis in the curved duct for turbulent pulsating flow at the De_{ta}= 3350, ω^+=18.5, A_1=1.3.

Figs. 5 and 6 show the result of secondary flow of turbulent pulsating flow in the central region of the duct along the z/b-axis.

In a flow with a dimensionless angular frequency (ω^+) of 18.5, the secondary flow shows very complex activity because the effect of the unsteady property along with the bend effect of the duct becomes distinct with the increase of De_{ta}. It can be observed through Fig. 5 (De_{ta}=3350, A_1=1.3) that the secondary flow movement near the upper and lower regions becomes complex in the entrance region of the curved duct and gets strong in the central region at bend angles of 30° and 60°. A strong secondary flow develops toward the inner wall from the outer wall in the region of bend angle of 30° [phase angle ($\omega t/\pi/6$)=0,6]. The intensity of secondary flow gets smaller, and the secondary flow is a complex phenomenon in the region at a bend angle of 60°. A secondary flow generated the strong flow toward the inner wall from the outer wall only during a minimum flow velocity at a bend angle of 90°. In the region of bend angle of 150°, a strong secondary flow develops toward the outer wall from the inner wall along the z/b-direction. The secondary flow decays gradually and becomes zero as it approaches the region of bend angle 180°, at the exit of the duct. In Fig. 6 (De_{ta}= 7380, A_1=0.6), A_1 relatively decreases and the viscous force increases in comparison with the inertia force, and the amplitude of secondary flow looks small when compared to that of Fig. 5. It is recognized that the form of the secondary flow is similar to the form of a steady flow because the component of steady flow gets strong when compared to the component of the oscillatory flow. It can be observed through Fig. 5 that a strong secondary flow is generated in the region of the upper wall at bend angle of 150°, and the secondary flow approaches zero in the region of bend angle 180°, the exit of the duct. In the case of turbulent pulsating flow, a strong secondary flow is fully generated in the regions of bend angles of 30° and 150°. Each of the conditions approach zero in the exit region at a bend angle of 180°.

3.3 Pressure distribution

The pressures were simultaneously measured at the inner and outer walls of the square cross-section from the entrance region of -20 D_h to the entrance region of 20 D_h. The basic pressure was fixed at the exit region of 20 D_h, and the difference of this pressure is shown.

In the figure, '◓' is the pressure on the inner wall and '◒' is the pressure on the outer wall. As seen in the figure, the pressure on the inner wall is less than that on the outer wall because of the centrifugal force produced by the curvature. Accordingly, the pressure increases toward the outer wall but decreases toward the inner wall. Therefore, [fso2] pressure gradient repeat gradually increase and gradually decrease in the exit region of curved duct.

Fig. 7 shows the pressure distribution of the turbulent pulsating flow in the entrance region of the curved duct. The turbulent pulsating flow pattern is compound flow as the steady and oscillatory flow. The viscous action to the inertia and it is classified as follows: When the viscosity accord with pressure term, quasi-steady region is appeared, when the pressure, viscosity and inertial term accorded the middle region is appeared also when the pressure accord with inertial term the inertial region is appeared [14]. If the time-averaged Dean number of the turbulent pulsating flow is increased, the phase of the inertial term proceeds in comparison with the phase of the viscosity term, and the phase of the pressure term changes into a delayed form. The boundary value for their three regions is obtained from the theoretical equation of the characteristic parameters by the same method as for the turbulent flow. The amplitude ratio of the inertial term about the amplitude of the pressure term increases along with the increase of the dimensionless

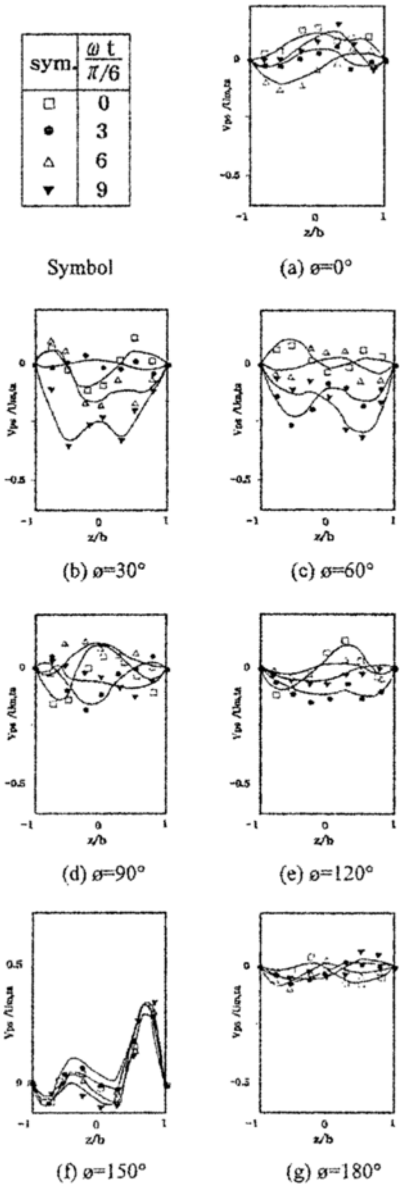
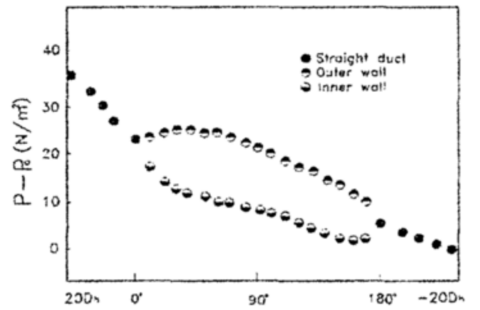


Fig. 6. Secondary flow distributions along the z * -axis in the curved duct for turbulent pulsating flow at the De_{ta}=7380, ω^+ =18.5, A_1=0.6.

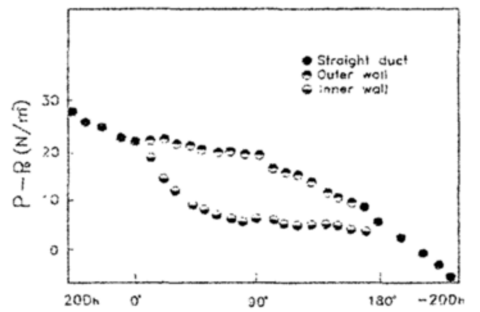
angular frequency, approaching theoretically a curved line. The amplitude ratio of the inertia term, the amplitude of the pressure term decreases as the measured point moves downstream. The more the oscillatory Dean number increases, the more the amplitude ratio of the viscosity term relative to the amplitude of the pressure term decreases. And it appears the phenomenon that the more the more oscillatory Dean number increases, the more differences between phases of the pressure gradient and the width cross-sectional mean velocity decrease. The pressure distri bution of turbulent pulsating flows was totally similar to those of the turbulent steady flows. In case of the middle region, the pressure difference was the largest close to the region of bend angle of 90°, and the pressure difference of the inner and outer walls was similar.

The pressure distribution of turbulent pulsating flows was totally similar to those of the turbulent steady flows.

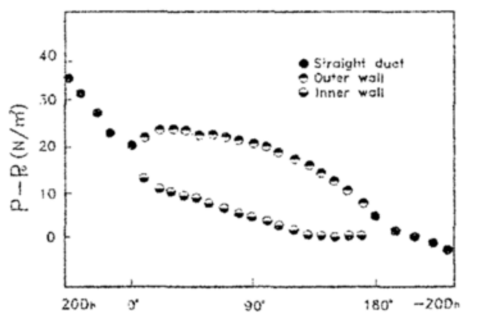
In case of the middle region, the pressure difference was the largest close to the region of bend angle of 90°. These experimental results agree relatively with those of Lee's [4] finding for a straight duct.



(a) Quasi-steady flow region



(b) Middle region



(c) Inertia region

Fig. 7. Pressure variation in the curved duct for the turbulent pulsating flow at the De_{ta}=3350, ω^{+}=18.5, A_1=1.3.

4. Conclusions

In a square cross-sectional 180° curved duct, the conclusions, which is obtained from experimental researches by using an LDV about turbulent pulsating flows, are as follows:

(1) In turbulent pulsating flow, when the ratio of velocity amplitude (A_1) is less than one, velocity fluctuation hardly occurs in a section but near the wall. Moreover, the shape of the axial follow by phase angle hardly changes. When the ratio of velocity amplitude (A_1) is 0.6, the change rate of velocity is slow and the velocity distribution is similar to that of the steady flow. The difference is that central flows of the duct show concavity due to oscillatory flow of unsteady property.

(2) A strong secondary flow is generated near the region of bend angles of 30° and 150° for a large ratio of velocity amplitude. A strong secondary flow develops toward the inner wall from the outer wall in the region of a bend angle of 30°[phase angle $\omega t/\pi/6$=0, 6]. The intensity of the secondary flow gets smaller, and the secondary flow is a complex phenomenon in the region at a bend angle of 60°.

The dimensionless value of secondary flow becomes weaker and approaches zero in the region of a bend angle of 180° regardless of the ratio of velocity amplitude.

(3) The amplitude ratio of the inertial term about the amplitude of the pressure term increases along with the increase of the dimensionless angular frequency, approaching theoretically a curved line. The amplitude ratio of the inertia term, the amplitude of the pressure term decreases as the measured point moves downstream. The pressure distribution of turbulent pulsating flow was totally similar to those of the turbulent steady flows. In the case of the middle

region, the pressure difference was the largest close to the region of bend angle of 90°, and the pressure difference of the inner and outer walls was similar.

Acknowledgment

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