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EFFECTS OF CORIOLIS FORCE ON DEVELOPING TURBULENT CHANNEL FLOW

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ABSTRACT

A rotating wind tunnel was designed to study the effects of Coriolis force on the turbulent boundary layer development in a rotating rectangular channel of low aspect ratio. Mean velocity and turbulence intensity profiles were measured by using a hot-wire anemometer and a new transmission system of electrical signals from a rotating apparatus to the stationary system. Some preliminary experimental results are reported.

INTRODUCTION

Many investigations concerning flow mechanism in the passages of centrifugal impellers have been reported for many years. The flow mechanism, however, is not yet understood completely because of the complexity of the flow which are affected by the rotation and the streamline curvatures of hub and shroud, from the axial to the radial direction, and blades in the tangential direction. To discern the effects of rotation from those of streamline curvature experimenters have investigated the flow in single rotating channels.

It is of common knowledge that the flow stability and the secondary flow play important roles in rotating channel flows. For example, the motion of fluid particles is stabilized in the boundary layer flow on the suction side (parallel to the axis of rotation) of the rotating rectangular channel, whereas on the pressure side, the motion of fluid particles is destabilized. At the same time, secondary flows from the pressure side to the suction side arise in boundary layers known as Ekman layers on the top and bottom walls (normal to the axis of rotation) because of the imbalance between the Coriolis force and the pressure force. Therefore, these are generally referred to as the stability effect and the secondary flow effect of Coriolis force, respectively.

Hill et al. (1962) and Moon (1964) studied the effects of rotation on turbulent boundary layers developing on the side walls of rotating rectangular channels of low aspect ratio. The measurements showed that on the suction side the boundary layer thickness increased substantially while on the pressure side the boundary layer is much thinner.

Wagner et al. (1972) reported the measurements of the longitudinal and secondary flow velocity profiles within a rotating rectangular channel of a 1: 2.7 aspect ratio. The presence of two longitudinal vortices which extended the length of the channel was confirmed. However, they did not attempt to measure the turbulence quantities.

Koyama et al. (1979) designed a rotating wind tunnel to study the stability effects of Coriolis force on two-dimensional boundary layers developing on the central portion of the side walls of a rotating rectangular channel of a 7 : 1 aspect ratio. Stability effects on two-dimensional, developing turbulent boundary layers in a rotating channel of a 4 : 1 aspect ratio were also reported by Watmuff et al. (1985). From the experimental results, the boundary layer development was found to be promoted on the pressure side and suppressed on the suction side, in comparison with the case of zero-rotation. These results showed the opposite trend to that obtained by Hill et al. (1962) and Moon (1964).

The objective of the present study is to make clear the secondary flow effects of Coriolis force on turbulent boundary layers developing on the walls of a rotating rectangular channel of low aspect ratio, and to offer the reliable experimental data on mean velocity and turbulence quantities which are desirable in numerical simulations of rotating channel flows.

An important difference between the present experiment and those by Hill et al.(1962), Moon (1964) and Wagner et al. (1972) is the inlet condition. If the flow within a rotating channel is irrotational then the velocity gradient would be twice as large as the angular velocity of the channel. Generally, the devices to have a constant velocity at the inlet of channel have an influence on the free stream which have also an influence on the boundary layer development.

APPARATUS AND INSTRUMENTATION

The general view of the experimental apparatus employed in the present study is shown in Fig. 1. A small wind tunnel was mounted on a turntable 2 m in diameter which was rotating about a vertical axis at a considerable speed. The tunnel can be rotated in either direction. Air, delivered to the rotating ducting attached under the turntable from the stationary ducting by a fan blower, flowed through the rectification section and the convergent section of 7.5 : 1 contraction ratio into the test channel. Rectification was effected by means of layers of honeycomb flow straighteners interspersed with screens. The channel had a cross section 40 mm high x 280 mm wide and a length of 760 mm. The flow rate was controlled by changing the rotational speed of the fan blower.

Flow in a rotating single channel, especially of low aspect ratio, is affected by a cross-flow which is equal to the circumferential velocity at the channel exit. Fowler (1968) suggested from a comparison of the experiments used a rotating channel installed a large box to the channel exit, and several similar channels each side of the test channel that the influence of adjacent channels, and the downstream flow field in general, has a large effect on the flow within a rotating channel. Therefore, in order to eliminate this obstructive influence in the study of Coriolis force effects, fences with a dimension of 110 mm high x 40 mm long was installed in 380 mm width on both sides of the test channel exit, and the rotating wind tunnel was covered with a transparent cylindrical fence. It was expected that these precautions reduce the effects of the cross-flow on the flow within the rotating channel to be negligible.

A constant-temperature hot-wire anemometer and hot-wire probes with a 5 μm tungsten wire, each inclined at a known angle to the main flow, were used for the measurements of the mean velocity and turbulence quantities. The hot-wire probe was traversed continuously by a traversing mechanism driven by a stepping motor, while the wind tunnel was rotating. Power for the operations of the hot-wire anemometer and the traversing mechanism as well as control signals were transmitted through the rotating slip rings.

Control unit of the hot-wire anemometer was mounted on the turntable. A new transmission system of hot-wire from the rotating system to the stationary system was designed to immunize the electrical noise because the signals must be sent through a very noisy environment to the stationary system for further processing. An analog signal of the hot-wire anemometer was converted to a frequency-modulated pulse. Then a light emitting diode(LED) placed in the rotating ducting at the end of the rotation axis of the wind tunnel was driven by the pulse. A photo signal of LED was changed to an electrical signal by using a photo-transistor placed in the stationary ducting on the extension line of the rotation axis. A phase-locked loop consists of a phase detector, a loop filter and a voltage-controlled oscillator was used to convert again a frequency output of the photo-transistor into an analog signal equal to a signal of the hot-wire anemometer mounted on the turntable. Details of the signal transmission system used in the present experiment have been reported by Koyama et al. (1989).

EXPERIMENTAL RESULTS AND DISCUSSIONS

Horizontal and vertical profiles of mean velocity and turbulence intensity were measured by using a hot-wire anemometer and a signal transmission system as mentioned above. The measurements were made at the six locations of 100 mm intervals, under the conditions of the channel inlet velocity equal to 10.0 m/s, and the angular velocities equal to 5.2 rad/s and 10.5 rad/s.

In this paper, Reynolds number Rex and rotation number Rox were used as the experimental parameters.

$$Rex = UcX/\nu \text{ and } Rox = \omega X/Uc \qquad (1)$$

Rotation number is a measure of the inertia force relative to the Coriolis force. In the eq.(1) X is the distance from the inlet of the channel, Uc is the velocity at center of the chanel and ω is angular velocity of the channel. In the present experiments, the ranges of Rex and Rox are from 6.67×10^4 to 4.40×10^5 and from 0 to 0.57, respectively.

Inlet condition

Hill et al. (1962), Moon (1964) and Wagner et al. (1972) were at great pains to establish a uniform velocity profile at the inlet to a test channel for all angular speeds of the channel. In the present experiments, however, we did not make efforts to establish a uniform velocity. Consequently, the system rotation imposes a linear velocity gradient along the transverse direction(y axis) on the flow. The velocity gradient of the potential flow within the rotating channel is equal to 2ω. As a fundamental idea, if the mean velocity and turbulence quantities are nondimensionalized by the corresponding velocity of the potential flow, one can evaluate them under the same criterion for the rotating and non-rotating cases. Therefore, in this paper, the mean velocity and turbulence intensity profiles were nondimensionalized by the hypothetical velocity Up(y), which was extrapolated from the velocity profile outside the boundary layer.

The turbulence intensity of the free stream at the channel inlet was less than 0.4 percent, which was found to be independent of rotation. Boundary layers on the walls at the channel inlet were always laminar under the usual operational conditions. To obtain the turbulent boundary layers, two tripping wires having an outside diameter of 1.0 mm and 1.5 mm were installed on the surface at the inlet and 75 mm upstream of the test channel.

Figure 2 shows the mean velocity and turbulence intensity profiles at the streamwise location equal to 100 mm nondimensionalized by Up(y) and the mean velocity at center of the channel Uc. For the angular velocity of 10.5 rad/s the mean velocity gradients were 19.2 1/s, 17.0 1/s and 14.5 1/s at the streamwise locations equal to 100 mm, 400 mm and 600 mm, respectively. When the quantitative evaluation of the effects of

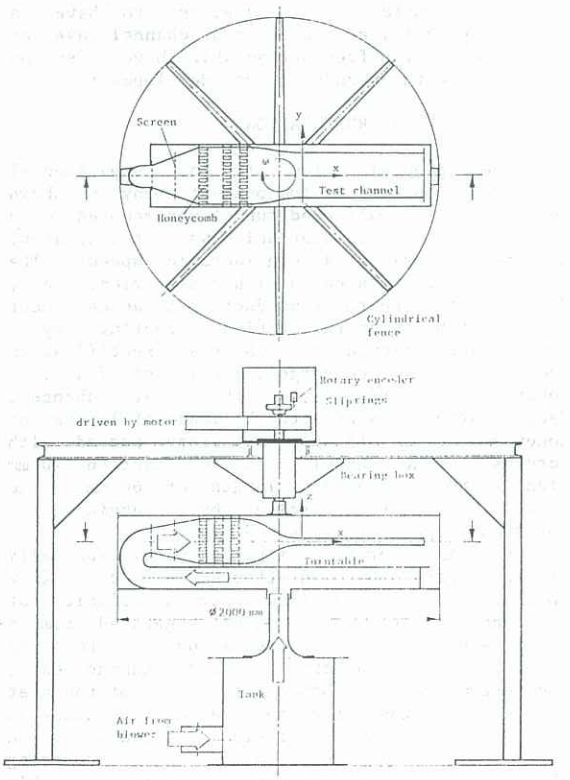

Fig.1. Tokyo Denki University Rotating wind-tunnel

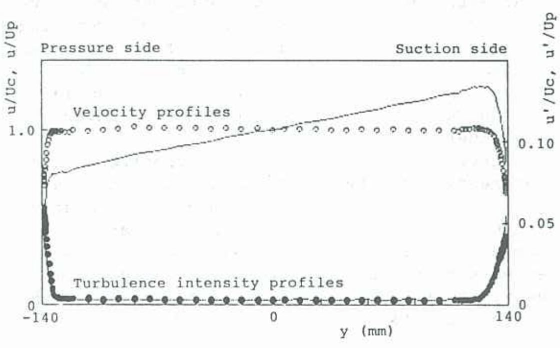

Fig.2. Mean velocity and turbulence intensity profiles at near inlet of rotating test channel

Coriolis force on boundary layers developing on the side walls of a rotating wide rectangular channel is required, one should compare the results with rotation with those without rotation by the same Reynolds and rotation numbers formed utilizing the velocity at the edge of boundary layer or the velocity extrapolated at the wall surface from the velocity profile of the free stream.

Horizontal profiles

Horizontal profiles of the mean velocity and turbulence intensity between the side walls of the rotating channel as well as the non-rotating channel are shown in Fig. 3, where, as in Figs. 4 and 6, the two cases are compared, the line representing the non-rotating channel flow and the circle the rotating flow. The measurement were made at middle-height of the channel. It is apparent that the boundary layer development is promoted on the suction side, while suppressed on the pressure side. The slop of the velocity profile increased in the vicinity of the pressure side wall and decreased on the suction side. This tendency is exaggerated with increasing the angular velocity and the distance from the inlet of the channel, i.e., with increasing Rox.

Similar observations have been reported by Moon (1964). However, at the final measuring station located 152 mm upstream from the outlet of the channel, substantial increase in boundary layer thickness on the suction side and sudden decrease on the pressure side, as compared with stations located further upstream, seem to indicate that the flow within the rotating channel was under the influence of the outlet.

On the suction side, the turbulence intensity decreases with increasing the streamwise distance, and is observed uniformly in the entire region of the boundary layer. On the pressure side, the peak value of the turbulence intensity is larger than that without rotation.

Experimental study on the stability effects of Coriolis force on two-dimensional boundary layer was performed by Koyama et al.(1979). From the experimental results, in contrast with the present experimental results, the boundary layer

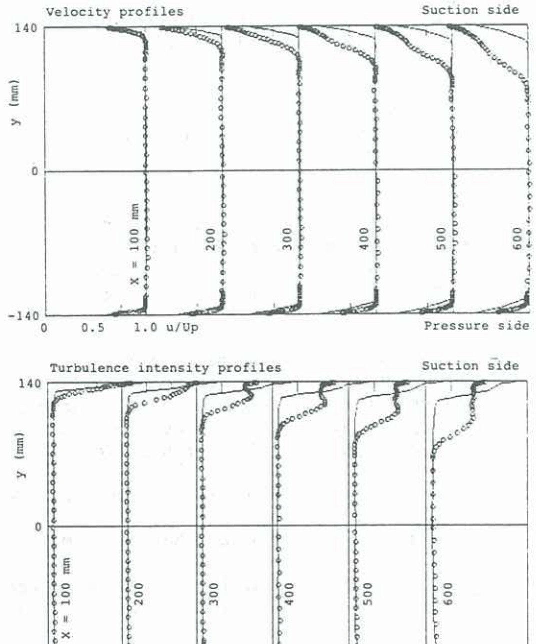

Fig.3. Horizontal profiles of Mean velocity and turbulent intensity at middle-height of channel

development was found to be promoted on the pressure(unstable) side and suppressed on the suction(stable) side, in comparison with the case of zero-rotation. Figure 4 shows the mean velocity and turbulence intensity profiles obtained by Koyama et al(1979). The measurements were performed at the streamwise location equal to 555 mm for the case of the angular velocity of 10.5 rad/s and also for the channel mean velocity of 10 m/s. Reynolds and rotation numbers were 3.80×10^5 and 0.45, respectively. The stability effects on the profiles are negligible on the suction side, and small on the pressure side.

The analogy between density stratified, curved streamline, and rotating turbulent flows has been discussed by Bradshaw (1969). In his literature, as an appropriate measure of the local stability for the case of rotating, parallel shear flow the gradient Richardson number was defined by

$$Ri = -2\omega(\partial u/\partial y - 2\omega)/(\partial u/\partial y)^2 = S(1 + S) \qquad (2)$$

where S is $-2\omega/(\partial u/\partial y)$ which represents the ratio of the local Coriolis force, $-2\omega u$, to the inertia force $u(\partial u/\partial y)$. The negative and positive signs of Ri correspond to the unstable(pressure) and stable(suction) sides, respectively. Figure 5 shows the variations of Ri, which are estimated from the results obtained by Koyama et al. (1979) for the cases at the channel mean velocity of 10 m/s, and at the angular velocity of 10.5 rad/s, 20.9 rad/s and 31.4 rad/s. The measuring location was equal to 555 mm. In this figure, y' and δ imply the distance from the wall surface and the boundary layer thickness. The circles in Fig. 5 show the present experimental results at streamwise location of 600 mm, and at angular velocity of 10.5 rad/s. From a comparison of the variations of Ri and the boundary layer developments with and without secondary flows it is found that the secondary flow effects on the boundary layer development overcome the stability effects, and substantial increase in boundary

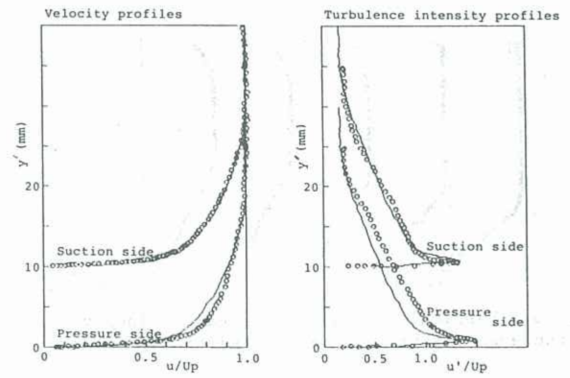

Fig.4. Mean velocity and turbulent intensity profiles in two-dimensional boundary layers

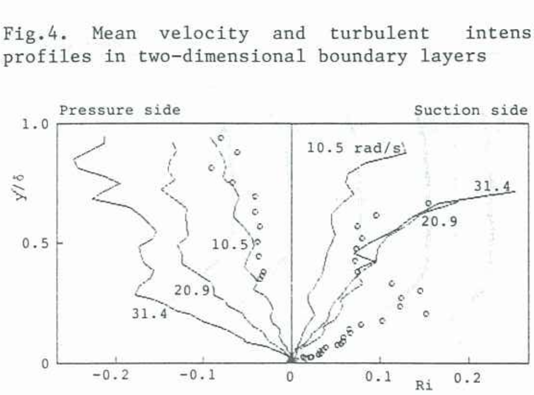

Fig.5. Variations of Richardson number in rotating boundary layers with and without secondary flows

layer thickness on the suction side, as compared with that without secondary flow, seems to stabilize the flow considerably near the wall.

Vertical profiles

The vertical profiles of mean velocity and turbulence intensity in rotating and non-rotating channel at middle-width of the channel are shown in Fig. 6. Figure 7 shows the vertical profiles of the transverse velocity component v corresponding to Fig. 6. The profiles are not symmetrical about the channel centerline. The thickness of boundary layer on the bottom wall is thicker than that on the top wall. It seems that a symmetrical converging nozzle to the test channel was designed, but at the channel inlet the turbulent boundary layers tripped by two wires were not the same characteristic flow. An inflection point of the profile of secondary flow velocity is at the middle of the boundary layer thickness. The magnitude of the secondary flow velocity is about 15 percent of the free stream velocity in the boundary layer at streamwise location of 500 mm, and about 17 percent in the outer region of the boundary layer. Although the secondary flows are observed, the effects on the development of boundary layers on the top and

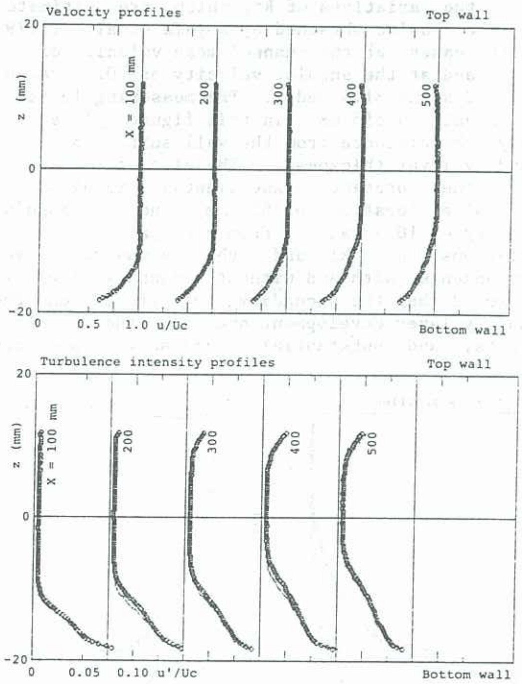

Fig.6. Vertical profiles of mean velocity and turbulence intensity at middle-width of channel

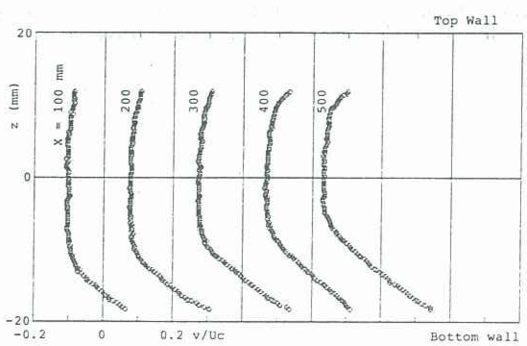

Fig.7. Vertical profiles of transverse velocity component at middle-width of channel

bottom walls are negligible.

Benton et al. (1966) obtained solutions for the flow consists of the geostrophic region, that is, the free stream region and the thin laminar boundary layer in rotating channels of arbitrary cross-section. In their analysis the secondary flow from suction side to pressure side occurred uniformly within the entire region of free stream flow. In the present experiment, the secondary flow velocity is observed also uniformly in the outer region of the boundary layer.

CONCLUSIONS

To clarify the secondary flow effects of Coriolis force on boundary layer development in a rotating channel of low aspect ratio. Conclusions reached as a result of present study may be summarized as follows:

(1) Secondary flow effects of Coriolis force on the development of turbulent boundary layer overcome the stabilizing effects on the suction side and the destabilizing effects on the pressure side, while are negligible on the top and bottom walls.

(2) Substantial increase in the boundary layer thickness on the suction side, as compared with that without secondary flows, seems to stabilize the flow considerably near the wall.

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