Laminarization of Turbulent Flow in the Inlet Region of an Axially Rotating Pipe *

Kenji NISHIBORI**, Koji KIKUYAMA**,
and Mitsukiyo MURAKAMI***

This paper describes the laminarization phenomenon of the flow in an axially rotating pipe when a fully developed turbulent flow is introduced into it. The rotating boundary layer is initially strongly stabilized by the centrifugal force due to the rotating velocity component, resulting in a laminarization of flow. This flow laminarization has been found to be more remarkable in the inlet region where a non-rotating inner core exists in the pipe section. The laminarized flow tends to be unstable as the flow goes downstream, and bursts of turbulence appear, which was also confirmed by the use of a flow visualization technique.

Key Words: Turbulence, Laminarization, Rotating Pipe, Inlet Flow, Velocity Distribution, Visualization

1. Introduction

The phenomenon of flow through a pipe rotating about its axis has plenty of engineering applications such as in flows in the inlet part of fluid machinery, rotating heat exchangers and cooling systems of rotors, and they have been investigated both experimentally and theoretically by several investigators⁽¹⁾⁽⁴⁾.

The present authors have studied the effects of pipe rotation on flow in the cases where an undeveloped flow^{(5)~(7)} and a fully developed flow^{(8)~(9)} were introduced into the rotating pipe. In the former case, pipe rotation causes a destabilization of the flow in the laminar boundary layer developing in the inlet region and brings about alternate spiral vortices. When the rotation speed of the pipe is increased, the spiral vortices are enhanced and bring about bursts of turbulence

and an upstream shift in the transition point from laminar to turbulent flow⁽⁷⁾. If the flow in the boundary layer is changed into a turbulent state by a step-ring installed at the entrance of the rotating pipe, the intensity of the turbulence in the boundary layer is seen to be largely suppressed by the pipe rotation in the downstream sections⁽⁶⁾.

When a fully developed turbulent flow is introduced into a rotating pipe, the hydraulic loss of the rotating pipe drops to below that obtained in a stationary pipe, and the axial velocity profile is deformed gradually into a parabolic one as the rotation rate is increased⁽⁸⁾⁽⁹⁾. These changes in the flow pattern are considered to be due to turbulence suppression caused by the centrifugal force of the swirling component. Such a turbulence suppression was confirmed recently by the experimental work of Yamada et al.⁽¹⁰⁾ and also by the use of the flow visualization technique by Cannon and Kays⁽²⁾. However, the details of the laminarization phenomenon of flow in the inlet region have been left unclarified.

This paper presents the experimental results on the laminarization phenomenon of flow in the inlet region of an axially rotating pipe. A laser doppler

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** Department of Mechanical Engineering, Nagoya University, Furocho, Chikusaku, Nagoya, 464, Japan

*** Department of Mechanical Engineering, Aichi Institute of Technology, Toyota, Aichi, 470-03, Japan

velocimeter and a flow visualization technique were employed when a fully developed turbulent flow was introduced into the rotating pipe.

2. Nomenclature

- a : pipe radius
 d : pipe diameter $= 2a$
 H_1 : shape factor based on a two-dimensional flow assumption

$$= \frac{1}{\theta_{x_1}} \int_0^a \left(1 - \frac{U}{U_e} \right) dz$$

 N : rotation rate $= V_0/U_m$
 r : radial distance
 Re : axial Reynolds number $= U_m \cdot d/\nu$
 U : time-mean axial velocity
 u : fluctuating velocity component in the x direction
 u' : root-mean-square (r.m.s.) value of $u (= \sqrt{u'^2})$
 U_e : free stream velocity
 U_m : mean axial velocity
 V : time-mean tangential velocity
 V_0 : peripheral speed of the rotating pipe wall
 x : axial distance from the entrance of the rotating pipe
 z : radial distance from the pipe wall $= a - r$
 θ_{x_1} : momentum thickness of the boundary layer in the x direction based on a two-dimensional flow assumption $= \int_0^a \frac{U}{U_e} \left(1 - \frac{U}{U_e} \right) dz$
 ν : kinematic viscosity of the fluid

3. Apparatus and Method

The experimental apparatus is shown schematically in Fig. 1. Water delivered from an over-flow tank flows successively through a rectifying tank, an upstream stationary pipe of 100 diameters length, a rotating pipe and a downstream stationary pipe. These pipes had the same diameter of 20.0 mm and a hydraulically smooth surface. The rotating pipe was driven by a variable speed motor. Measurements of velocities were made by a laser doppler velocimeter at sections various distances from the pipe inlet. The

Fig. 1 Schematic outline of experimental apparatus

measuring section of the pipe was replaced by a lucite tube, through which the laser beams could be applied, and a maximum 50 ppm of milk was added as a tracer. In order to visualize the flow transition, aluminum flakes (0.007 percent by volume) were mixed in the fluid. The experimental ranges of the axial Reynolds number and rotation rate were $5 \times 10^3 \leq Re \leq 3 \times 10^4$ and $0 \leq N \leq 5$, respectively.

4. Experimental Results and Discussions

4.1 Distributions of time-mean velocities

Figures 2(a) and (b) show the time-mean velocity profiles at various sections in a pipe rotated at rates of $N=1.0$ and 3.0 , respectively, when a fully developed turbulent flow of $Re=10^4$ is introduced into the rotating pipe. The axial velocity curve corresponding to the stationary state ($N=0$) is shown by a chain line. At each value of N the axial velocity distribution U/U_m exhibits a rather flattened profile at the section $x/d=11$ near the pipe inlet compared with the inlet flow profile shown by a chain line. This tendency becomes remarkable at the downstream section, $x/d=36$, and there seems to be a potential core in which the radial gradient of the axial velocity profile is almost absent near the pipe center. At sections further downstream, $x/d \geq 68$, however, the axial velocity profiles tend to be deformed into a projecting form near the pipe center and they approach a parabolic curve, shown by a broken line, as N increases, as is shown in Fig. 2(b), indicating a reverse transition of flow to a laminar state.

As the flow goes downstream, the tangential velocity component V/V_0 near the wall region is developed gradually due to the effect of the rotating wall. At the downstream sections, $x/d \geq 118$, however, the rate of change in V/V_0 along the pipe axis becomes less and less, and the velocity profile exhibits a parabolic one, shown by a broken line, similar to an almost saturated state of flow, regardless of the value of N .

The flatness of the axial velocity profile near the pipe center of the inlet region, as described above, is probably due to the fact that the shear stress is decreased by the turbulence suppression caused by the centrifugal force of the swirling flow component, and the axial velocity profiles in the boundary layer are similar to those observed in the laminar inlet flow developing in a stationary pipe, as shown in Fig. 3(a). A remarkable similarity of the theoretical velocity profiles in the laminar boundary layer is observed over the inlet region if z/θ_{x_1} is taken as a dimensionless value of the radial distance from the pipe wall. In Fig. 3(b) the axial velocity profiles U/U_e for $N=1$ and 3

(a) $N=1$

(b) $N=3$

Fig. 2 Changes in velocity profiles along the pipe

are plotted against z/θ_{x1} , where U_e and θ_{x1} denote the free stream velocity and the momentum thickness based on an assumption of two-dimensional flow. When a fully developed turbulent flow ($Re=10^4$) is introduced into the pipe at the rotation rate of $N=1$, the axial velocity distribution U/U_e at the section $x/d=11$ exhibits a profile intermediate between the profile of turbulent pipe flow (as shown by a chain line) and that of laminar pipe flow (a broken line) in a stationary pipe. At the downstream section $x/d=36$, the velocity profile U/U_e approaches a laminar state profile, exhibiting the stabilizing effect of the swirling velocity component. However, at sections further downstream, $x/d \geq 68$, the velocity profiles change gradually from laminar to turbulent. When the rota-

(a) Laminar inlet flow in a stationary pipe

(b) Turbulent inlet flow in a rotating pipe

Fig. 3 Changes in axial velocity profile inside the boundary layer

tion rate is increased to $N=3$, the axial velocity profiles coincide well with the laminar state curve in the region $36 \leq x/d \leq 118$. At the most downstream section, $x/d=168$, however, the velocity profile is seen to deviate slightly from the laminar flow pattern. From the results described above, it may be concluded that the laminarization of flow in the rotating pipe becomes remarkable inside the boundary layer near the pipe wall of the inlet region.

4.2 Shape factor

The changes in the flow pattern in the boundary layer can be understood more clearly by examining the shape factor obtained from its velocity profile.

Figure 4 exhibits the changes in the shape factor H_1 of the axial velocity profile along the pipe axis. The calculated value of H_1 in the laminar state of flow in a stationary pipe has a nearly constant value of $H_1 = 2.5 \sim 2.6$ over the inlet length, provided the flow is assumed to be two-dimensional. For comparison, the value of $H_1 = 2.5$ corresponding to a saturated laminar flow, in which a potential core disappears, is shown by

Fig. 4 Changes in shape factor H_1 along the pipe ($Re = 10^4$)

a broken line. When a fully developed turbulent flow enters the rotating pipe, the stabilizing effect of the pipe rotation becomes remarkable due to the effect of the abrupt acceleration of flow in the tangential direction and the value of H_1 increases rapidly in the inlet region. In this case H_1 increases with an increase in N . This means that the flow pattern in the boundary layer gradually approaches a laminar profile as N

Fig. 5 Changes in shape factor H_1 along the pipe ($Re = 3 \times 10^4$)

Fig. 6 Flow visualization ($Re = 10^4$, $N = 1$)

Fig. 7 Flow visualization ($Re=10^4$, $N=3$)

increases. The shape factor H_1 has its maximum at a distance of about $30d$ from the entrance, and it decreases asymptotically to a certain value in the downstream sections. This may be due to the fact that the turbulence in the boundary layer is increased again by the destabilization effect due to the increase in the boundary layer thickness.

Figure 5 exhibits the changes in H_1 along the pipe axis at $Re=3 \times 10^4$. The H_1 curves show a tendency similar to those for $Re=10^4$. H_1 is seen to increase abruptly just after the pipe inlet when $N > 0.5$ and it decreases gradually after its maximum point at a certain distance. A comparison of the H_1 curves in Figs. 4 and 5 reveals that the increase in H_1 near the pipe inlet is more remarkable at $Re=10^4$ than at $Re=3 \times 10^4$.

4.3 Flow visualization

In order to confirm the changes in the flow pattern in the inlet region of the rotating pipe, a flow visualization experiment was carried out using a lucite pipe in the measuring sections. Aluminum flakes were mixed in the fluid and slit-light was passed through the pipe axis. Figure 6 exhibits the photographs taken at various sections when $N=1$ and $Re=10^4$. In the region $x/d=12 \sim 28$ near the pipe inlet (Fig. 6(a)), the non-rotating core existing in the central region of the pipe

Fig. 8 Mechanism of cyclic bursts
($Re=5 \times 10^3$, $N=5$, $x/d=94 \sim 110$)

(a) $x/d=11$ (b) $x/d=36$ (c) $x/d=168$ Fig. 9 Distributions of turbulence intensity ($Re=3 \times 10^4$)

is attenuated as the flow proceeds downstream and a laminarized flow can be seen in the thin layer near the pipe wall. At the downstream sections $x/d=36 \sim 52$ (Fig. 6(b)), a turbulent state of flow appears intermittently in the laminarized layer, namely, a "burst of turbulence" phenomenon is clearly observed. This entrainment of turbulent bursts is maintained along the channel. At the sections further downstream $x/d=94 \sim 110$ (Fig. 6(c)), the non-rotating core in the central part of the pipe disappears and the rotating layer reaches the pipe center; the velocity profiles which correspond to these are shown in Fig. 2(a). In this region, masses of turbulent spots generated by the bursts at the upstream section are diffused downstream and no distinct laminar portions of flow can be distinguished in the figure. The turbulent fluctuations periodically alter the flow pattern as shown in Fig. 6(c). At the most downstream sections, $x/d=170 \sim 186$ (Fig. 6(d)), however, the flow pattern is again returned to a normal turbulent state.

The stabilizing effect of pipe rotation becomes dominant when the rotation rate is increased to $N=3$ as shown in Fig. 7. In the inlet regions, $x/d=12 \sim 28$ (Fig. 7(a)) and $x/d=36 \sim 52$ (Fig. 7(b)), the flow in the wall layer with a swirling flow component turns almost into a laminar state. At the downstream sections, $x/d=94 \sim 110$ (Fig. 7(c)), the laminar state of flow is maintained over the sections $x/d=94 \sim 110$. In this region the central core has completely disappeared and the frequency of bursts is significantly low. At the sections further downstream, $x/d=170 \sim 186$ (Fig. 7(d)), however, the flow in the rotating pipe is destabilized and the turbulence intensity of the bursts is enhanced. From the flow visualization results presented above, it is found that the laminarized boundary layer in the inlet region is destabilized at the downstream sections and the flow is changed into a turbulent state. This fact agrees well with the changes in shape factor H_1 along the pipe axis as shown in Figs. 4 and 5.

In order to investigate the mechanism of the bursts of turbulence, photographs were consecutively taken at a chosen region in the rotating pipe. Figure 8 presents photos which were taken at about 0.6 second intervals at the sections $x/d=94 \sim 100$, when $Re=5 \times 10^3$ and $N=5$. These photos represent a cyclic change in the flow states: the laminarization of flow (Fig. 8(a)), the beginning of instability (Fig. 8(b)), the turbulence due to bursts (Fig. 8(c)), and the relaminarization of flow (Fig. 8(d)). From this, it appears that the occurrence of the bursts is attributable to a vortex break-down in the flow⁽¹²⁾.

4.4 Turbulent fluctuations

From the flow visualization mentioned above, it

has been found that the flow in the inlet region of the rotating pipe exhibits a complicated flow pattern which changes intermittently. Figures 9(a)~(c) show the changes in the distributions of the turbulence intensity in the axial direction, measured at various sections for different values of N . In the measurements of the turbulence intensity by laser velocimeter, the axial Reynolds number was increased to $Re=3 \times 10^4$ in order to get sequential outputs by increasing the number of milk particles passing the measuring section. The rotation rate was in the range of $0 \leq N \leq 1$, where the flow was still in a normal turbulent state. Figure 9(a) illustrates the distributions of the turbulence intensity u'/U_e at the section $x/d=11$. The values of u'/U_e are decreased with an increase in N over the section, except near the pipe axis where they remain almost unchanged in the range $0 \leq N \leq 1$. At the section $x/d=36$ (Fig. 9(b)), pipe rotation causes a more remarkable decrease in the values of u'/U_e over the section, including the pipe center. This will be due to the decrease in the production of turbulent energy, $-uw\partial U/\partial z - vwr\partial(V/r)/\partial z$, because of the absence of a velocity gradient. If the rotation rate is increased to $N=1$, then the values of u'/U_e decrease approximately to one half of those in a stationary state ($N=0$). The results at the most downstream section, $x/d=168$, are plotted in Fig. 9(c). Although the values of u'/U_e are seen to decrease uniformly over the section with an increase in N , the rate of the decrease is lower than that observed at the upstream section, $x/d=36$.

Figure 10 shows the changes in the distributions of turbulent intensity in the axial direction along the pipe axis, when $N=1$. The chain line indicates the distribution in the stationary state ($N=0$) corresponding to the flow condition just before the rotating pipe inlet. At the section $x/d=11$ near the entrance, the value of u'/U_e near the pipe wall is seen to be decreased, showing the stabilizing effect due to the swirling flow. The values of u'/U_e are a minimum at the downstream section, $x/d=36$. At the sections further downstream, $x/d \geq 68$, however, u'/U_e begins to increase conversely. In this figure, the changes in the axial time-mean velocity profile U/U_m along the pipe are also plotted for comparison. From the fact that the velocity profile U/U_m becomes a projecting form at the pipe center as the section proceeds downstream, it was thought, in past studies, that the flow in a rotating pipe was always laminarized as the flow went downstream. However, as is seen in the foregoing results of turbulence measurements, it has been proven that a laminarization of flow in a rotating pipe becomes more remarkable in the inlet region, near the entrance, where the swirling motion of the

Fig. 10 Changes in turbulence intensity along the pipe ($Re=3 \times 10^4$)

flow does not reach the pipe center and in the sections further downstream, pipe rotation may cause a destabilizing effect. The above result coincides fairly well with the results of the changes in the shape factor H_1 in Fig. 6.

5. Conclusions

A laminarization phenomenon of flow in the inlet region of an axially rotating pipe was investigated when a fully developed turbulent flow was introduced into it. The results obtained are summarized as follows:

(1) When the rotation speed of the pipe is increased to a certain value, a laminarization phenomenon is observed in the rotating layer in the inlet region near the entrance ($x/d \approx 20 \sim 60$). This laminarized flow, however, is destabilized as the flow proceeds downstream and characteristic bursts of turbulence in the rotating pipe occur.

(2) When laminarization occurs in the rotating layer near the pipe wall, the axial velocity profile becomes flat near the pipe axis and is similar to that observed in the laminar inlet flow developing in a stationary pipe. Thus, the flow pattern inside the

boundary layer near the pipe wall can be estimated by the use of the shape factor H_1 based on the axial velocity profile.

(3) Under the same rotation rate conditions, the laminarization of flow in the inlet region is promoted as the axial Reynolds number is decreased.

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