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TURBULENT FLOW IN AN AXIALLY ROTATING PIPE (EFFECT OF INLET SWIRL)

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Abstract

The effect of the inlet swirl on the flow in an axially rotating pipe was investigated experimentally. The tangential component of velocities given by a honeycomb located at the pipe inlet shows a forced vortex type profile and the axial velocity component is approximately in a fully developed turbulent flow pattern. The tangential velocity profile, which exhibits a forced-vortex one, is deformed into a concave type, and the axial velocity profile becomes more convex as the flow goes downstream. The velocity profiles in this rotating pipe are also compared with those obtained without the inlet honeycomb.

By use of a visualizing method the stabilizing effect of the pipe rotation on the flow is confirmed to be more remarkable in the pipe without the inlet honeycomb.

1. Introduction

When fluid enters a rotating channel, it receives a rotational component of velocity and the distribution of the velocities across the sections are changed and, accordingly, the hydraulic loss in the channel receives also a change. Similar flow phenomena can be observed in axial type turbomachines, rotary type heat exchangers, and cooling systems of rotors.

The flows entering the rotating channels may have a pre-rotational component in some cases and the component will affect the flow patterns in the rotating channels.

The present authors[1)] have measured the velocity distributions and hydraulic

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loss in an axially rotating pipe when a fully developed turbulent flow without swirling component is introduced to the pipe and found that the axial velocity profile tends to be a parabolic form as the flow goes downstream and that the hydraulic loss becomes small. These changes in the flow will be attributable to the suppression of turbulence within the pipe, which is brought about by the centrifugal force due to the swirling flow component given by the moving wall.

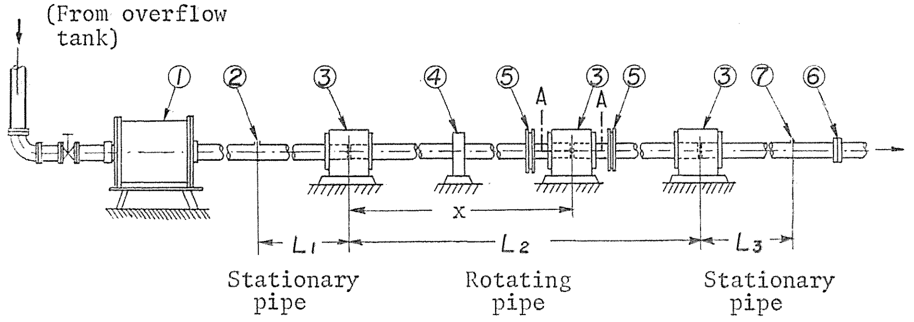
Changes in the velocity profiles and hydraulic loss have been calculated by the present authors[2] by use of a modified mixing length theory. Giving a forced vortex type tangential velocity component to the flow within the inlet section of an axially rotating pipe, Yamada and his co-worker[3] measured changes in the flow pattern along the pipe, and found that this forced vortex motion could not be maintained in the downstream sections, in which a rotating field was existing. The tangential velocity distributions in far downstream sections show a parabolic form, showing a drop in the velocity curve between the wall and center of the section. The reason why this drop occurs in the rotating pipe remains still unexplained.

The changes of the flow pattern along an axially rotating pipe were measured when a short honeycomb was provided in its inlet section, and the results were compared with those without the inlet honeycomb.

2. Experimental Equipment

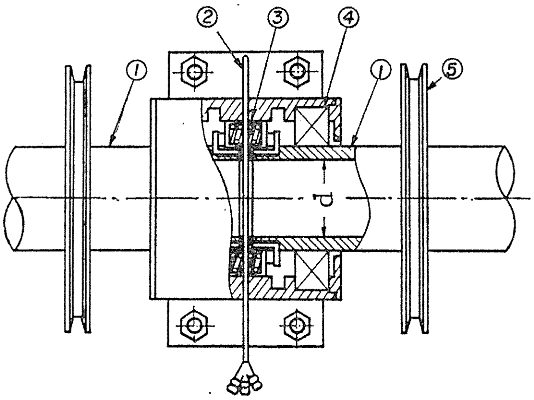
A schematic outline of the experimental equipment and detailed measuring section are shown in Fig. 1 and 2, respectively. Water from an overflow tank was led to a rectifying tank, from which it was introduced through a stationary straight duct to a rotating pipe.

Diameters of the rotating pipe employed in the experiment were 54, 32, and 20mm, respectively. In order to give a tangential velocity component to the liquid flowing through the rotating pipe, a honeycomb of a short length was provided at the inlet section of the rotating pipe, by which a forced vortex type motion just the same as that of the rotating pipe field could be given to the fluid. This honeycomb was composed of thin tubes as shown in Fig. 3. To check the effect



1. Rectifying tank 2. Upstream pressure tapping
3. Bearing 4. Bearing 5. Pulleys
6. Orifice 7. Downstream pressure tapping

Fig. 1. Schematic of experimental equipment.



1. Rotating pipe
2. Pitot tube
3. Stationary ring
4. Bearing
5. Pulley

Fig. 2. Details in measuring section (A-A section in Fig. 1).

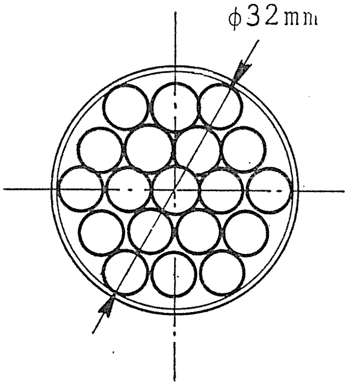


Fig. 3. Section of inlet honeycomb.

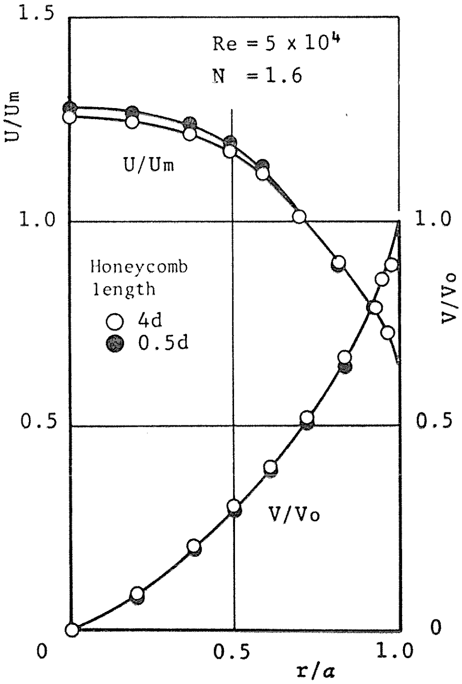


Fig. 4. Changes in velocity profiles for different honeycomb length at the section of $x/d=105$.

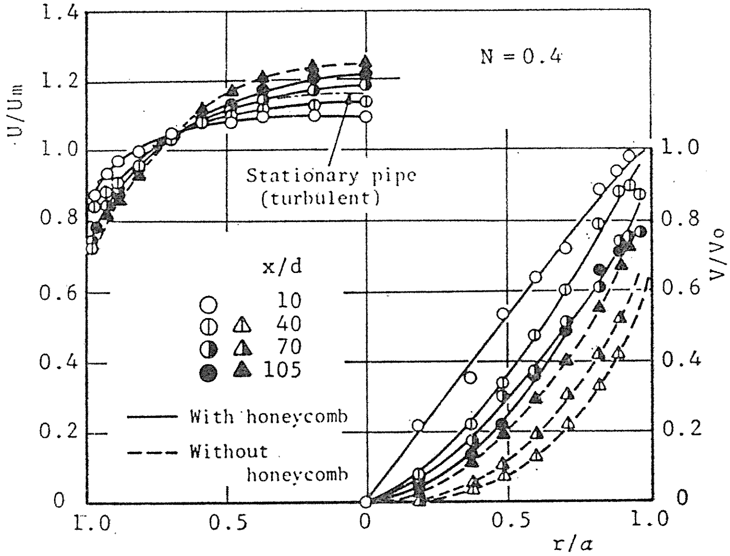
of the honeycomb length on the downstream flow, the experiments were carried out with two kinds of honeycomb of different axial lengths, $0.5d$ and $4.0d$, respectively. The result is shown in Fig. 4. As there is a negligible difference between the two honeycombs in the flow pattern in the rotating pipe, the honeycomb with the length of $4.0d$ was only used in the experiments.

Velocities in the rotating pipe were measured by a cylindrical Pitot probe, the diameter of which was 2.0 mm. The probe was located both in the stationary (Fig. 2) and rotating system, and the results obtained by respective locations of the Pitot probe were compared.

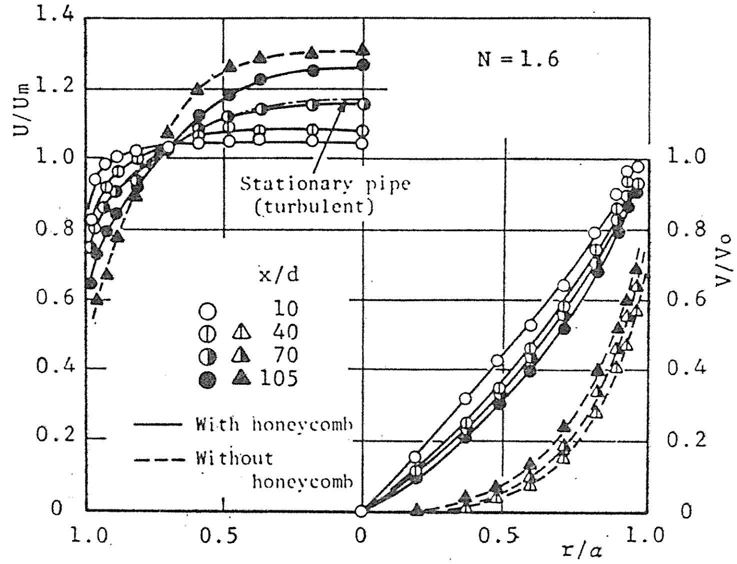
3. Experimental Results and Discussions

3. 1. *Velocity distributions*

Figures 5 (a) and (b) show the changes in the tangential velocity profiles along the rotating pipe for the rotation rate of $N=0.4$ and 1.6, respectively, when the pipe with the inlet honeycomb is employed. The rotation rate N is defined by the



(a) For $N=0.4$



(b) For $N=1.6$

Fig. 5. Changes in velocity profiles along the pipe.

ratio V_0/U_m, where V_0 is the peripheral velocity of the rotating pipe and U_m the mean flow velocity. In the same figure, the velocity profiles in the pipe without the inlet honeycomb are indicated by dotted lines, and also the axial velocity curve in a fully developed turbulent flow without the swirling flow component is shown by a chain line.

When $N=0.4$, the axial velocity distribution shows a rather flattened profile at the section $x/d=10$, just downstream of the inlet honeycomb. The flatness of the profile becomes less as the section goes downstream and the curve exhibits a more convex form. In the tangential velocity distributions, an exact forced-vortex profile shown by a straight line (obtained in the upstream section $x/d=10$) changes its form into a parabolic one as the section goes downstream and the profile approaches to the velocity curve without the inlet honeycomb.

According to the results about the change in the tangential velocity curves as described above, the flux of angular momentum is seen to be diminished downstream in the rotating pipe, and it will be probable that the tangential velocity component of the liquid near the wall is decelerated along the pipe axis.

When the rotating rate N is increased from 0.4 to 1.6, the change in the axial velocity profiles along the pipe axis has the same tendency but the profiles themselves show more flattened forms near the pipe center.

The tangential velocity profiles in this case do not also exhibit an exact forced flow pattern at the downstream sections of $x/d=40\sim105$, but a parabolic form having a concave between the center and wall. This concavity is not so remarkable as in the pipe without the inlet honeycomb even in the section of $x/d=105$. As the tangential velocity profiles in Figs. 5 (a) and (b) show a concave one, the following relation can be assumed between the tangential velocity and the radial distance r as

$$V/V_0=(r/a)^n$$

where V and a denote the tangential velocity of liquid and the radius of the pipe, respectively. To check the above expression, the measured values of the tangential velocities V/V_0 are plotted in a logarithmic scale against r/a in Fig. 6. The results for the pipe without the inlet honeycomb are also plotted by dotted lines in the same figure for $N=0.4$. The above expression is well confirmed by the experiments. The value of n changes as the axial distance x/d increases and the tendency of this change is opposite in the both cases with and without the inlet honeycomb. In the case with the inlet honeycomb n increases with x/d, but in the case without the inlet honeycomb it decreases as x/d is increased. In the sections of $x/d>100$, the difference in n in the two cases may substantially be negligible and n may be taken approximately to be 2. The effect of the rotation rate N on n is shown in Fig. 7, where the values of n are plotted against x/d. In the pipe with the inlet honeycomb, the change of n along the pipe axis is rather small. The value of n in upstream sections is nearly to unity, which means that the tangential velocity distribution is in an exact forced vortex motion due to the inlet honeycomb constrainment. On the other hand, in the pipe without the inlet honeycomb, n has a much larger value in upstream sections and it decreases approximately to 2 as the flow goes downstream. The rate of change in n along the pipe axis becomes less as N increases, which will be resulted from the fact that in a pipe rotating with higher value of N the suppression of the turbulence will be

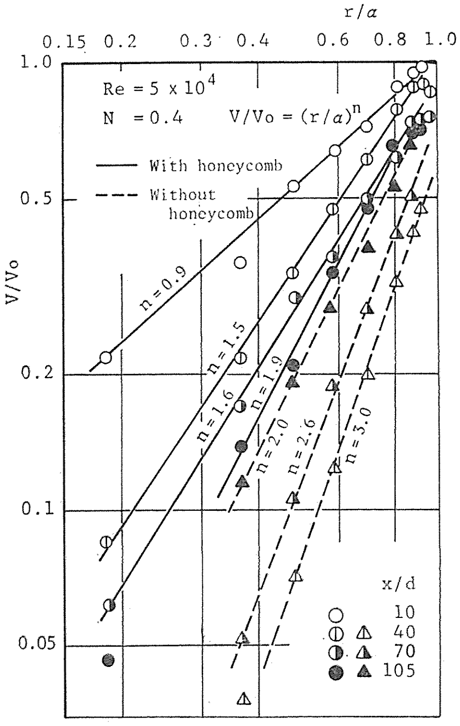


Fig. 6. Relation between tangential velocity and radial distance at the various sections.

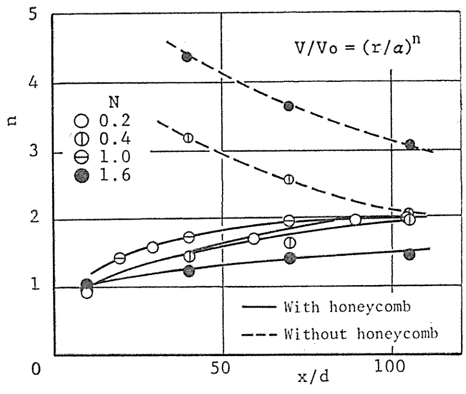


Fig. 7. Changes in value of n along the pipe.

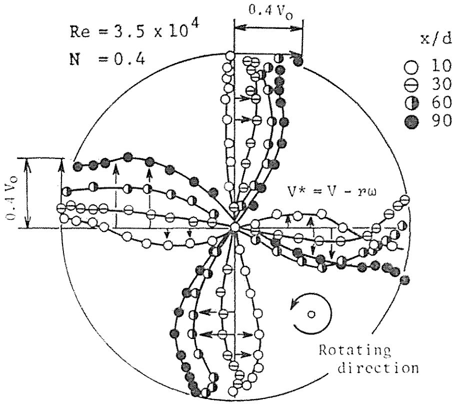


Fig. 8. Distributions of tangential velocity relative to the pipe wall.

promoted by an increase of centrifugal force effect. The results explained above are all those obtained by the Pitot probe located in the stationary system. To check these results, measurements of velocities were made with the Pitot probe mounted on the rotating pipe.

An example is shown in Fig. 8, where tangential velocities relative to the rotating pipe, $V^*=V-r\omega$, where ω denotes the angular velocity of the pipe, are plotted for various sections, when $N=0.4$ and $R_e=3.5\times10^4$. At the section of

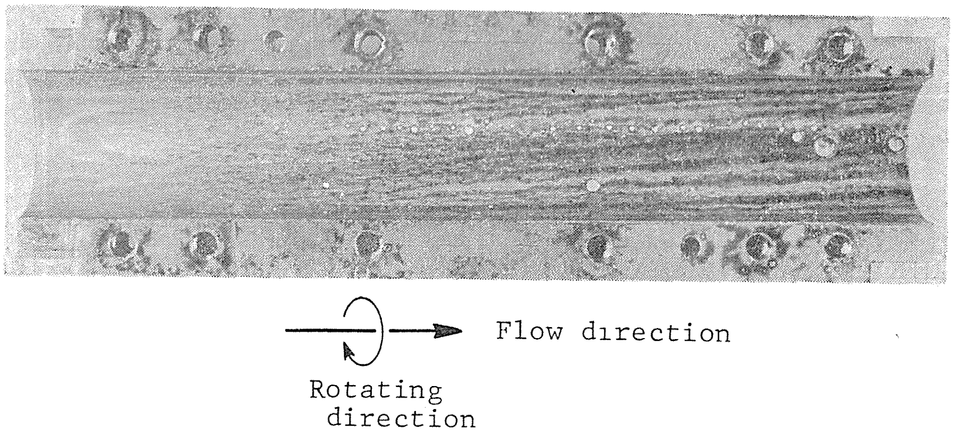
$x/d=10$, just downstream of the honeycomb, the relative rotational velocity at every measured point is very small.

At the section of $x/d=30$, negative values of V^* dominate the section, indicating a slower angular velocity of the fluid than the rotational speed of the field. This deffect of the tangential velocities becomes remarkable at the section of $x/d=90$, a considerable downstream section.

From the above fact it may be concluded that the angular momentum flux given by the inlet honeycomb can not be maintained in an axially rotating pipe to the downstream sections but is reduced in a certain amount. This phenomenon occurs only in a turbulent condition of flow and if the flow is laminar the tangential velocity component given in the initial section may be unchanged both in the form and strength to the downstream sections.

3. 2. Oil Surface Flow Patterns

To examine the flow phenomena near the pipe wall in a more detailed degree, the streamlines near the wall were visualized by means of oil surface method. An example is shown in Fig. 9, which is a photo taken in the axial range of $x/d=15\sim 21$ when $N=0.3$ and $R_e=3.7\times 10^4$. The limiting streamlines as is seen in dark lines in the figure are those obtained by coating oil uniformly on the pipe wall and explosing it to the flow for about fifteen minutes. The streamlines lie not parallel to the pipe axis but incline slightly so as to have a little larger tangential velocity than the rotating field velocity.



Eig. 9. Oil surface flow pattern for $N=0.3$ at the sections of $x/d=15\sim 21$ ($Re=3.7\times 10^4$).

Consulting this result and remembering the fact that the decrease in the angular momentum flux occurs in the downstream sections in the rotating pipe as is seen in Fig. 5 (a), it may be considered that the fluid particles flowing on the pipe wall will exert a negative torque to the pipe wall, the magnitude of which will correspond just to the amount of angular momentum lost in the liquid. This will be an inherent phenomenon in an axially rotating pipe and may probably be caused by a coupled effect of the turbulent fluctuation of velocities and the system rotation. This phenomenon can only seen in a relatively narrow region near the rotating pipe inlet. In a more downstream region, the streamlines are seen to be almost parallel to the pipe axis. In this region, the tangential shear component is greatly suppressed and further decrease in the angular momentum flux can not be seen.

3. 3. Pressure Gradient along Channel

Figure 10 shows the change in the wall pressure along the pipe when the rotation rate is $N=0.4$, 0.8 and 1.6, respectively. The solid lines express the results with the inlet honeycomb and the dotted lines are those without the honeycomb. For reference, the pressure gradient in a stationary pipe is shown by a chain line for the same Reynolds number. In the rotating pipe without the inlet honeycomb, the pressure gradient is decreased as N increases. The degree of this decrease becomes much less in the pipe having the inlet honeycomb and the pressure curve becomes almost parallel to that in a stationary pipe if the measured sections lie in the range of $x/d \geqq 60$.

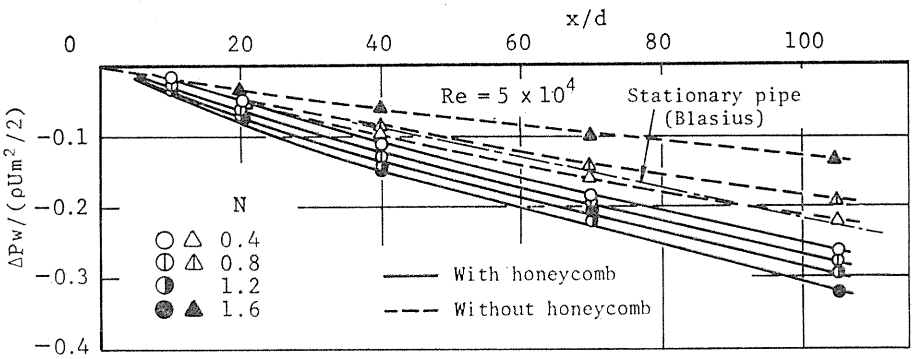
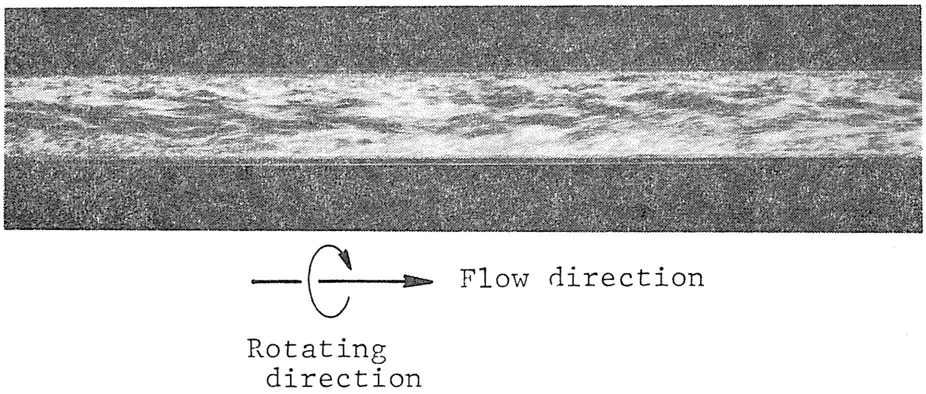


Fig. 10. Drops of wall pressure along the pipe axis.

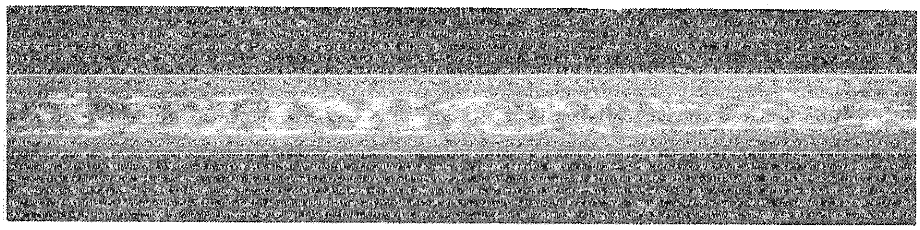
3. 4. Flow Visualization

As is supposed from the results in Fig. 10, the existence of the inlet honeycomb has much effects on the flow downstream in the rotating pipe. To examine the flow pattern in more details, a rotating pipe made of a lucite tube was employed and the flow was visualized by mixing alminium flakes into the liquid.

Figs. 11 (a) and (b) show the photos of the flow patterns inside the rotating pipes with and without the inlet honeycomb, respectively. In the pipe without the inlet honeycomb, a laminar state of flow can be seen in the layer near the pipe wall as is seen in Fig. 11 (b). This laminar flow pattern will be due to the stabilizing effect brought about by the strong acceleration of flow in the tangential direction. In the pipe with the inlet honeycomb such an intensive acceleration does not exist and the flow laminarization also does not occur within the visualized sections. In these sections concave profiles in the tangential velcoity distribution as shown by dotted lines in Fig. 5(b) do not prevail.



(a) With inlet honeycomb.



(b) Without inlet honeycomb.

Fig. 11. Flow visualization for $N=2$ at the sections of $x/d=40\sim50$ ($Re=10^4$).

4. Conclusions

The results obtained in this study can be summarized as follows:

(1) When a turbulent flow accompanying a rotational velocity component is introduced to an axially rotating pipe, the distribution of the tangential velocity component is deformed in the downstream sections into another concave form and in this process the axial velocities tend to become a parabolic profile.

(2) Stabilizing effect due to the pipe rotation on the flow is more remarkable in the case when the entering flow has no tangential component of velocities.

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