Hydraulic Losses and Flow Patterns of a Swirling Flow in U-Bends*

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In the past, the hydraulic losses and the flow patterns in pipe bends when a fully developed flow enters the bend were studied. But, practically, most of the flows are not uniform in the axial velocity component and accompanied with a swirling component, which causes different hydraulic losses and flow patterns in the bends. Such problems remain almost unsolved at present.

In the present paper, the effects of curvature and surface roughness on the hydraulic losses and flow patterns of a swirling flow in U-bends are studied.

1. Introduction

A pipe line of a fluid machine or other hydraulic plants has often many complicated bend portions and the flow pattern will be distorted much after the bends. If this distorted flow is introduced into a bend located downstream, the hydraulic loss and velocity distribution in it will be quite different from those in a single bend located in a long straight pipe line. In the past, many studies on hydraulic losses of bends have been made, but most of them are related to a fully developed inlet flow. The authors have investigated experimentally(27) and theoretically(30) hydraulic losses and flow patterns of bends for the case of a flow with non-uniform velocity distributions accompanied with weak swirls. But many problems remain unsolved in relation to those of bends for inlet flow distortion.

In the present work, the effects of a swirling inlet flow on hydraulic losses and flow patterns of the U-bends were investigated experimentally, in which the strength of swirl in the approaching flow was variously changed. The inlet swirl produces two special types of swirling flows in the U-bend, and the reasons why those special flows are caused are discussed here. The effects of bend radii and surface roughnesses on energy losses of the U-bends were investigated in detail.

2. Nomenclature

\[ p : \text{pressure} \]
\[ \Delta p' : \text{dimensionless pressure difference between outside and inside walls of a plane parallel to bend plane} \]
\[ \Delta p_w' : \text{dimensionless mean wall pressure energy difference between inlet and outlet of a bend} \]
\[ Q, \text{V_m} : \text{flow rate} (\text{m}^2/\text{s}), \text{and mean axial velocity in a bend measured by the orifice meter} \]
\[ \Delta E', \Delta K', \Delta p_T' : \text{dimensionless total, kinetic and pressure energy differences between inlet and outlet of a bend, respectively} \]
\[ \Delta E', \Delta K', \Delta p_T' : \text{divided by bend length} \pi(R/\text{r_w}) \left( \Delta E'/\pi(R/\text{r_w}), \Delta K'/\pi(R/\text{r_w}), \Delta p_T'/\pi(R/\text{r_w}) \right), \text{where} R/\text{r_w} \text{ of mitre bend is zero, but the length of mitre bend is} 13.72\text{r_w} \]
\[ R : \text{radius of bend curvature} \]
\[ r, \text{r_w} : \text{radial distance of a point and radius of pipe wall} \]
\[ S : \text{center line length of bend (Fig.1)} \]
\[ V_z, V_w' : \text{dimensionless axial and peripheral velocities} (=V_z/\text{V_m} =V_w/\text{V_m}) \]
\[ 0_c : \text{angular position of eccentric center of the flow in pipe section (Fig.1)} \]
\[ \varepsilon : \text{height of surface roughness element} \]
\[ \rho : \text{density of fluid} \]
\[ \zeta : \text{total loss coefficient of U-bend (27)} \]
\[ \theta : \text{deflection angle of a bend (Fig.1)} \]
\[ i : \text{inlet section} \]
\[ o : \text{outlet section} \]

3. Experimental apparatus and procedure

A schematic diagram of the experimental apparatus is shown in Fig.1(a). Water from the head tank is introduced into the rectifying tank and the water is given a swirl component by the guide vanes located at the outlet of the rectifying tank. The strength of the swirl is adjusted by a change of the guide vane angles. The U-bends tested are set at the length 15d downstream from the outlet of a guide vanes. A straight pipe is jointed to the outlet of the U-bend. The swirling motion which is generated by the guide vane is of a free vortex type. To make clear the effects of vortex types on the hy-
draulic losses and the flow patterns, experiments in regard to the forced vortex type motion in the U-bends are also carried out. The forced vortex is generated by a multi-twisted S-bend pipe (six 90°-bends combined). Dimensionless curvatures of the U-bends, \( R/\tau_w \), are 0, 3, 4 and 6. The U-bend with \( R/\tau_w=0 \) is composed of two 90°-mitre bends and the total bend length is 13.72\( \tau_w \), Fig.1(a). To investigate the effects of wall roughness, the inside surfaces of bends are roughened artificially by sea sands. The relative roughnesses of bends are given in Table 1. The measuring sections for velocity are located at the angles of \( \theta=0°, 45°, 90°, 135° \) and \( 180° \), in the U-bend. To measure the velocity distributions within the U-bends, a cylindrical Pitot tube with three holes (tube diameter= 3.025 mm, hole diameter = 0.3 mm) is traversed along the axes of N,P, NP and PN, respectively as shown in Fig.1 (c).

The flow rate obtained with a Pitot tube is about 6% in maximum and 3-4% in mean values larger than that of the orifice. Eight pressure holes are drilled on the peripheral wall of each bend, and the wall pressures at the inlet and outlet of the U-bends are also measured. Although the tests are mainly run at a Reynolds number of approximately \( 10^6 \), the effect of Reynolds number is also investigated (see 5.4).

4. Equation to express experimental results

The notations \( \Delta p' \), \( K' \), \( \Delta K' \), \( E' \), \( \Delta E' \), \( M' \) and \( \Delta M' \) used in the present work are the same with those in refs. (2), (3), (Eq.(8)) (3), (Eq.(25)) (37) (see 5.2). To estimate the pressure energy flux \( P_1 \) passing through the inlet and outlet sections of the U-bends from the measured wall static pressures and velocities, the pressure \( p_m \) at the radial distance \( r_m \) the pressure energy flux \( P_1 \) across the section and the dimensionless pressure head \( p' \) per unit volume can be calculated, respectively, by the following relations:

\[
p_{m} = \frac{p_{m}}{r_{m}} \]  
\[
P_1 = \frac{8}{\pi} \frac{u_{m}^{2} \rho_{m} \pi}{2} \]  
\[
P_{1} = \rho_{m} \left( P_{1} \right) = \frac{1}{2} \rho \frac{v_{m}^{2}}{2g} \]  

where the flow at the inlet and outlet sections is assumed to be a non-uniform one accompanied with a symmetric swirl.

5. Experimental results and discussion

5.1 The decay of swirling flow and its flow patterns in U-bends

The four kinds of velocity profiles \( \left( \rho = 0.5, 0.7, 1.4, 3.05 \right) \) used in the experiments are shown in Fig.2. The right hand side in Fig.2 shows the axial velocity distributions and the left hand side the peripheral velocity distributions. In the flow with the maximum swirling intensity, a reverse axial velocity is seen to be originated in the central region of cross section and the peripheral velocity distribution becomes a free vortex type in the outside region. The decays of the angular momentum \( M' \) in the swirling flows are shown in Fig.3. If the curvature ratios of the U-bends \( R/\tau_w \) are equal to or larger

Table 1 Kinds of U bends (\( \theta=180° \)), \( \tau_w=d/2 \)

<table>
<thead>
<tr>
<th>kinds of bends</th>
<th>U bend</th>
<th>U mitre bend</th>
</tr>
</thead>
<tbody>
<tr>
<td>kinds of wall surfaces</td>
<td>cast brass bend</td>
<td>fine machined bend</td>
</tr>
<tr>
<td>( R/\tau_w )</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( \epsilon ) mm</td>
<td>0.205</td>
<td>0.205</td>
</tr>
<tr>
<td>( d ) mm</td>
<td>53.8</td>
<td>53.8</td>
</tr>
<tr>
<td>( \epsilon / d )</td>
<td>0.0038</td>
<td>0.0038</td>
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than 4, and the swirling flows have a maximum strength of $M'_1$=3.05, the decays of swirling flows follow a wavy process and the mean values of these decays show a nearly similar gradient to that experienced in the straight smooth pipe.

On the other hand, if the curvature ratios of the U-bends are small, namely, in sharp bends, the decays of swirling flows become larger than in the straight smooth pipe. When the swirling strength $M'_1$ is 1.4, the decay is still wavy.

But the mean gradient is larger than that of the straight smooth pipe, and the gradient increases as the radius of curvatures of the U-bends decreases. When the swirling flow ($M'_1=0.5$) is of a compound vortex type, the decay of $M'$ is not wavy, and it is gentle at first and then becomes steep. The process of the decay of the forced vortex type flow ($M'_1=0.7$) is similar to the above one. When the swirling flow enters a U-mitre bend ($R_/tw=0$) which is composed of two 90°-mitre bends, the greater part of the swirling components diminishes around the first corner. This phenomenon

Fig. 2 Axial and peripheral velocity distributions of swirling flows at inlet of U-bend

Fig. 3 Decays of swirling flows in U-bends

ordinate: dimensionless angular momentum flux, $M'$

abscissa: angular distance of a section (θ) and bend length (S/tw), respectively, are changed

$M'$, R_/tw and θ/d, respectively, are changed

Fig. 4 Axial and peripheral velocity distributions in U-bend when a strong swirling flow, $M'_1$=3.05, enters U-bend ($R_/tw=6$)

up-column: equi-axial velocity lines (Vz)

middle-column: peripheral velocities (Vθ)

down-column: pressure differences between outside and inside walls of planes parallel to bend surface (Δp)
occurs irrespective of the swirl strength. The swirling flows in the U-bends can be classified into two types from the tendencies of decays of swirling flows shown in Fig.3.

(1) A flow with wavy pattern of the angular momentum decay.

(2) A flow without wavy pattern of the angular momentum decay.

In the following, the causes of these two types of flows will be qualitatively explained from the results of the velocity distributions. Flow type (1). The velocity distributions of flow type (1), which corresponds to symbol $N(M' = 0.05)$, are shown in Fig.4. The up-, middle- and down-columns in Fig.4 correspond to the axial and the peripheral velocities, and the pressure differences $\Delta p'$ between outside and inside bend walls of parallel planes to bend surface, respectively. It is known from the axial velocity distributions that there is a vortex core in the central portion of each section and the flow in the region between the wall and vortex core corresponds nearly to a potential flow in which the axial velocity is low in the outside of bend surface and high in the inside. To be more specific, the center of the vortex core is located at the outside near the center of each section and it flows in a coiled pattern* along the axis of U-bend.

On the other hand, the maximum axial velocity exists at the right hand side of P axis in the section of $\theta = 0^o$, and moves to the left hand side in the section of $\theta = 45^o$ and to the right hand side at the section of $\theta = 90^o$, but it remains always in the inside region of bend. The motion resembles that of a pendulum. The motions of the maximum axial velocity portion and the vortex core are closely related. Namely, if the maximum velocity portion moves to the right, the vortex core moves to the left. A model of this motion is shown in Fig.5(b). The wavy broken line in Fig.5(a) expresses the path of the vortex core center. Figure 5(b) shows a model of equi-axial velocity lines at the sections of $\theta = 90^o$ and $135^o$ as seen in Fig.4. This wavy flow will be caused by a shift of the vortex core center which moves in a coiled from along the center line of the U-bends. If it occupies the left hand side in the section, the axial velocity on the right hand side increases. This motion is repeated downstream. Distribution of wall pressure differences $\Delta p'$ between outside and inside as measured parallel to the bend surface will be changed by the pendulum motion of water flow as shown in the down-column of Fig.4. A new secondary flow in the boundary layer near

* The coiled pattern of vortex center is found in the swirling flow of straight pipe, too.

Fig.5 Explanation of flow model when a strong swirling flow enters U-bend

(a) axial velocity distribution on bend surface
(b) equi-axial velocity lines at $\theta = 90^o$ and $135^o$ sections (c) expresses an arbitrary point on line AB (see Fig. 11 in literature (2))
(c) $\Delta p'$ distributions (wall pressure differences between outside and inside walls of parallel planes to bend surface)
(d) peripheral velocity distributions at inlet section

the wall will be caused by the differential wall pressure $\Delta p'$ as described above. The directions of secondary flow are indicated by thick arrows in the peripheral velocity distributions in the middle-column of Fig.4. The models of pressure distributions $\Delta p'$ in the sections of $\theta = 90^o$ and $135^o$ and the directions of secondary flow due to $\Delta p'$ distributions in Fig.5(c) are indicated by arrows in Fig.5(b). Figure 5(d) shows a model of peripheral velocity in the inlet of U-bend.

Flow type (2). Figure 6 shows the velocity distributions corresponding to the symbol $N(M' = 0.5, R_{w}w = 6)$ in Fig.3. The up-, middle- and down-columns in Fig.6 are the equi-axial velocity lines, the peripheral velocities and $\Delta p'$ distributions, respectively. The swirl strength of this flow is weak and 1/6 times as large as the
maximum strength. In this case, the type of swirling is of a compound vortex. The vortex core which existed in the inlet region of the U-bend disappears in the downstream region of $\theta=135^\circ$, and at the same time a low velocity region develops in the inside wall of bend. The maximum velocity moves from the inside of bend to the outside when $\theta$ increases. The peripheral velocity has only one directional component in the inlet region, but a reversed peripheral component (counter-clockwise direction) begins to develop in the middle section of the U-bends and comes to occupy about half the section at the outlet region of the U-bends. The force indicated by thick arrows given in the peripheral velocities, Fig.6 is caused by the pressure difference $\Delta p'$ (down-column in Fig.6) and this pushes the fluid in the boundary layer near the wall in counter-clockwise direction. This reverse force in the middle section of the U-bends is stronger than the clockwise swirling flow which existed already in the upstream sections. As the result, a reverse swirling component develops and in this process the clockwise swirling flow is abruptly weakened. The low velocity fluid is accumulated near the wall where both the clockwise and the counter-clockwise components impinge, and the axial velocity decreases (see Fig.6, $\theta=90^\circ$-$180^\circ$). Accordingly, the axial velocity in the central portion of the section increases, and then the vortex core disappears. Thus, the coiled motion and the pendulum motion of water flow come to an end. In this stage the high velocity region is in the outside of bend and the flow becomes an oscillatory type one accompanied with asymmetric double spiral secondary flows. This type of oscillatory flow is shown in detail in refs. (2) and (3).

5.2 The effects of wall roughness on the decay of swirling flow
The decays of swirling flows in the U-bend ($R/w=3$) with sand-roughened wall are expressed by $X(c/d=0.0121)$ and $\nabla (c/d=0.0371)$ (dotted lines) in Fig.3. The strength of swirling flow at the inlet is $M'=1.4$. These results are compared with those of symbol $O (c/d=0.0038, R/w=3$ brass cast U-bend) in Fig.3. The tendencies of decays of swirling flows in these three kinds of U-bends are almost the same in the sections upstream of $\theta=90^\circ$, but in the region of $\theta>90^\circ$ the roughness effects become evident and in the section of $\theta=180^\circ$ the strength $M'$ of cast brass bend is about two times as large as that of $c/d=0.0121$ sand-roughened bend and about seven times that of $c/d=0.0371$ sand roughened bend. In Fig.3, the results for a straight pipe ($c/d=0.008$) are also shown by four dotted lines. The decays in the U-bends are much larger than those in the straight pipe. The velocity distributions at the sections of $\theta=90^\circ$ and $180^\circ$ in the U-bend with maximum roughness are expressed in Figs. 7(a) and (b). To make a comparison, the results of brass cast bends are plotted by broken lines. In Fig.7, the vortex core which is located concentrically on the center of the inlet section $\theta=0^\circ$ (the figure is omitted) moves on the NP(+) axis at the section of $\theta=90^\circ$ and disappears at the outlet section $\theta=180^\circ$. The maximum axial velocity which is located on NP(+) axis at the section of $\theta=90^\circ$ moves on PN(-) axis at the section of $\theta=180^\circ$, and a considerably high elevation of velocity is seen on N(+) axis. A separation develops from the inside wall of section $\theta=90^\circ$ and grows fairly large at the section of $\theta=180^\circ$, but no separation occurs in the brass cast bend. In case of rough surface bend, the peripheral velocity
components on the outside region of section \( \theta = 90^\circ \) are as large as those on the inlet section, but a reverse peripheral velocity begins to develop in the inside region. In case of brass cast bend, the strength of peripheral velocity component within the outside region of section \( \theta = 90^\circ \) is nearly the same as that of the bend with rough wall and no reverse peripheral component occurs in the inside region. The peripheral components decrease sharply at the outlet section, \( \theta = 180^\circ \), in the rough surface bend. On the other hand, the decay of swirling motion in the cast bend is small, and reverse peripheral components are seen to occur on PN(+) axis of outlet section of \( \theta = 180^\circ \).

From the above results, it may be concluded that in the bend with rough wall the one-directional swirling flow decreases sharply and the secondary flow caused by the wall pressure difference \( \Delta P' \) dominates easily in the U-bend. Moreover, a separation occurs in the inside of bend and the low velocity region extends downstream. The secondary flow is further accelerated in consequence.

5.3 Hydraulic losses due to the swirling flow in U-bends

Energy losses caused in various kinds of U-bends are described in Fig. 8. The strength of swirling flow at the inlet section, \( M_1' \), and the radius of the bend curvature \( R/R_w \) are changed in the experiment. The total energy loss \( \Delta E' \) is maximum at \( R/R_w = 0 \) when the inlet swirl has considerably high strength of \( M_1' = 3.05 \) and 1.4, and decreases gradually as \( R/R_w \) increases. If the inlet swirl is as weak as \( M_1' = 0 \) and 0.5, \( \Delta E' \) also takes a maximum at \( R/R_w = 0 \) but it decreases to a minimum at \( R/R_w = 3 \), and then this process is repeated as \( R/R_w \) increases. Results of the forced vortex type swirling flow (\( M_1' = 0.7^\circ \)) are denoted by symbol \( \bullet \). The tendency of energy loss of the forced vortex flow is almost similar to that of the compound vortex one of \( M_1' = 0.5 \). For reference, the dimensionless mean wall pressure energy differences \( \Delta P_w' = \Delta P_w / (R/R_w) \) between the inlet and outlet sections of U-bend

\[ \epsilon/d = 0.0038 \]

![Fig. 7](image_url)

**Fig. 7** Axial and peripheral velocity distributions of swirling flow in sand roughness U bend (solid lines, \( \epsilon/d = 0.0371 \), \( R/R_w = 3 \)) and brass cast U bend (broken lines, \( \epsilon/d = 0.0038 \), \( R/R_w = 3 \)) at \( \theta = 90^\circ \) and 180° sections.

*The swirling strength of a forced vortex type flow of \( M_1' = 0.7 \) is one of the strongest vortices which are caused in bend lines with several 90°-bends combined.*

![Fig. 8](image_url)

**Fig. 8** Effects of bend radius ratio \( R/R_w \) on \( \alpha P_w', \Delta E' \), \( \Delta R' \) and \( \Delta E' \) for U bends, \( \epsilon/d = 0.0038 \)
are described in Fig. 8(a). $\Delta P_{w}'$ is larger than $\Delta E'$ in all the regions except the cases of $M_1' = 1.4$, $\Delta P_{w} = 6$ and $M_1' = 3.05$, $R/R_{w} = 3$. The total bend loss coefficients $\zeta = 1/R(\pi R_w)$ obtained by Ito are expressed by a thick broken line for comparison.

The values of $\zeta$ are larger than those of $\Delta E'$ in this experiment, but Ito's results are nearly equal to $\Delta P_{w}'$. The total energy loss $\Delta E'$ is given by the sum of pressure and kinetic energy differences, $\Delta P_{w}'$ and $\Delta R'$. $\Delta P_{w}'$ and $\Delta R'$ are shown in Fig. 8(b).

$\Delta P_{w}'$ and $\Delta R'$ change in complicated forms with the strength of inlet swirl $M_1'$. $\Delta R'$ becomes minus in some cases if the swirl is as weak as, $M_1' \leq 0.7$. This will be due to the fact that the centrifugal force due to the curved motion in the bend increases as the bend becomes sharper, and a more intensive secondary flow occurs. This secondary flow is superposed on a one-directional swirling flow which already exists in the bend inlet, resulting in an increase of the kinetic energy in the bend outlet. The effects of wall relative roughness $c/d$ on energy losses are shown in Fig. 9, where the curvature ratio of U-bend and the relative roughness are $R/R_w = 3$ and $c/d = 0.0036$, 0.0211 and 0.0371, respectively. Figure 9(a) shows the relationships among $\Delta E'$ (solid line), $\Delta P_{w}'$ (a dotted line), $c/d$ and $M_1'$. For comparison, the friction coefficients of rough straight pipes measured by Nikuradse are described by broken lines. The values of Nikuradse correspond to a straight pipe having the length of pipe radius $r_w$ when $Re = 10^5$. Both of the loss coefficients for the straight pipe and the U-bends are almost the same if $M_1' \leq 0.7$ and $c/d$ is small, but the values of the U-bends become larger as $c/d$ increases. $\Delta E'$ of the U-bends increases largely as $M_1'$ increases. $\Delta P_{w}'$ is nearly equal to $\Delta E'$ if $c/d$ remains small, but the values of $\Delta P_{w}'$ exceed those of $\Delta E'$ if $c/d$ is larger. Figure 9(b) shows the relationships among $\Delta P_{w}'$, $\Delta R'$, $c/d$ and $M_1'$. $\Delta R'$ (broken line) increases for all values of $M_1'$ when $c/d$ increases. On the other hand, $\Delta R'$ decreases as $c/d$ increases except the case of a strong swirl of $M_1' = 3.05$. $\Delta R'$ shows negative values in some cases when $M_1' \leq 0.7$. This phenomenon is the same one of $\Delta R'$ becoming minus in Fig. 8(b).

Figure 10 shows the relationships between $\Delta P_{w}'$ and $\Delta R'$ explained in Figs. 8 and 9, in which the symbols $\Delta(R/R_w=0)$, $\Delta(R/R_w=3)$, $\Delta(R/R_w=6)$ denote the results for the brass cast bends ($c/d = 0.0038$) and $\Delta(R/R_w=0.0037)$. $\Delta(R/R_w=3)$, $\Delta(R/R_w=0.0371)$ and $\Delta(R/R_w=0.0038)$ denote the values for the rough bends.

It is seen that $\Delta P_{w}'$ is about one half of $\Delta P_{w}'$. The line of $\Delta P_{w}' = \Delta P_{w}'$ in this figure, corresponds to the case of a fully developed turbulent flow without swirl component in a circular straight pipe. It is known from the above results that the pressure energy difference $\Delta P_{w}'$, assumed from wall pressure between the inlet and outlet sections of the bend does not express the true pressure energy loss between the sections, when the flow is accompanied with swirling components. The relationship between $\zeta = (\Delta E' - \lambda (\pi R_d))$ and $\eta = \Delta P_{w}' - \lambda (\pi R_d)$ in the straight pipe is obtained experimentally by Murakami et al., where $\zeta$ and $\eta$ are the factors denoting the additional amounts of the total energy loss and wall pressure energy caused by the swirling components, and $\lambda$ is the loss coefficient of a fully developed pipe flow with no swirling, which corresponds to $\zeta = 0$ in Fig. 11. Their results are described
by curves (1) ($0 < \eta < 0.8$) and (2) ($\eta = 0.8$) in Fig.11. The author's results of $\zeta$ and $\eta$ between inlet and outlet of U-bends are denoted by $\bullet$, $\ast$, etc. in the figure. The values of $\zeta$ and $\eta$ in the U-bends are nearly equal to those of swirling flows in the straight pipe if the wall roughness is comparatively small ($c/d = 0.0038$) and $3.5R/s < 6$, but $\eta$ considerably deviates from the curve (2) (for straight pipe) to the right because $\Delta P'w$ becomes larger than $\Delta E'$ when $c/d = 0.0038$.

5.4 The effects of Reynolds number (Re) on energy loss of U-bends

The effects of Reynolds numbers on $\Delta P'$, $\Delta E'$, and $\Delta R'$ are shown in Fig.12, in which Reynolds numbers are changed from $4 \times 10^6$ to $1.2 \times 10^7$. The effects of Reynolds number are seen to be very small.

6. Conclusions

The hydraulic losses and flow patterns of swirling flows in the U-bends are examined experimentally. The results obtained can be summarized as follows.

(1) If the strength of inlet swirl is sufficiently strong, i.e., $M' > 0.7$, the swirling flow in the U-bends is a special type of a one-directional rotational motion, in which the angular momentum flux decays in wavy forms along the center line of the U-bends. If the strength of inlet swirl is weak, i.e., $M' < 0.7$, the angular momentum flux in the U-bends decays gradually at first, and then sharply, along the bend center line.

(2) The patterns of swirling flows in the U-bends are much affected by the curvature and roughness of the U-bends.

(3) The total energy losses in the U-bends are changed in a complicated manner by the strength of the inlet swirl, bend curvature and wall roughness, and the losses can't be estimated from the loss co-eficients of smooth bends found in a fully developed turbulent inlet flow without swirl component.

(4) The effects of the swirling flow components in the U-bends are almost independent of Reynolds numbers, when $Re > 3.5 \times 10^4$.

Acknowledgement

The authors wish to express their thanks to Prof. Mitsukyo Murakami, Department of Mechanical Engineering, Nagoya University.

References