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Hydraulic Losses and Flow Patterns in Bent Pipes*

(Comparison of the Results in Wavy Pipes and Quasi-coiled Ones)

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A coiled pipe, a helically bent pipe and a wavily bent pipe are used in practical engineering for many purposes.

In this report, the relationships between hydraulic losses and flow patterns are investigated in regard to wavily bent pipes and quasi-coiled pipes which are constructed with many 90° elbows or 90° bends with small curvature ratios, R/r_w=1, 3 and 6, respectively. The results of wavy pipes are compared with those of quasi-coiled pipes. The reasons why wavily bent pipes are adequate for application to the heat exchanger are explained.

1. Introduction

The pipes with bend combinations are much used in the heat exchangers, since the curved path in the bends promotes the mixing in flow for active heat transfer. The bend combinations employed currently are coiled pipes or wavy pipes curved in one plane.

The wavy pipes are recently recognized as suitable for the heat exchangers with high efficiency. For the bend ducts, many theoretical and experimental studies have been performed, but most of them are limited to the case of smoothly coiled pipes with a relatively large radius of curvature and data on the wavy pipes and the coiled ones with smaller radius of curvature are few.

The present authors(1) and Rowe(2) have studied the flows in S-shaped wavy pipes composed of two or three bends, and Pydenko(3) measured hydraulic loss and velocity distribution in wavy pipes composed of many curved elements having a curvature ratio R/r_w from 7 to 12 and a bend angle from 34° to 132°. Murata(4)(5) analyzed a laminar flow in wavy pipes curved in a sine form and Yamashita et al(6). made a theoretical analysis of a flow in wavy pipes composed of several 90° mitre bends. However, the data in regard to the wavy pipes with a relatively small radius of curvature ($R/r_w \leqq 6$) are not sufficient for suitable design of heat exchangers. Also, the relation between the wavy pipes and the coiled pipes remains unsolved.

In the present work, the relation between the hydraulic losses and flow patterns in wavy bent pipes and quasi-coil pipes composed of several bend elements are investigated. The curvature ratios of the bends employed are 1, 3 and 6, respectively.

2. Nomenclature

d : diameter of pipe $= 2r_w$
g : acceleration of gravity
n : number of bends
R : radius of curvature
V_m: mean velocity assumed from orifice readings
v_z, v_α : axial and peripheral velocities

3. Experimental apparatus and procedures

The general arrangement of the test apparatus is shown in Fig.1. A constant pressure head is maintained in the test pipe line by using a head tank. The water pumped up to the head tank is conveyed successively to the orifice meter, the rectifying tank, the test bend and to the straight portions of the pipe line.
The wall pressures p_1 and p_2 are measured at two sections L_u=5d upstream and L_d=210d downstream from the bent portion. The bent pipes used in the experiment are com-

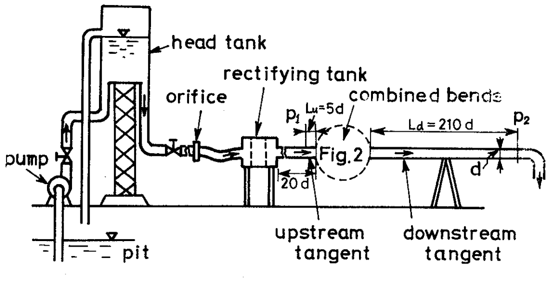

Fig.1 Schematic diagram of the experimental apparatus

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posed of 90° screw type commercial elbows*1 having a curvature ratio of $R/r_w=1$, and of 90° special bends of zinc casting having the ratios of $R/r_w=3$ and 6. Ten or more bend elements of the same kind are connected in series. The angle of combination ϕ_n is shown in Fig.2. The typical forms of the bent pipes used in this experiment are shown in Fig.3. Figures 3(a) and (b) are U-shaped and S-shaped wavy bent pipes and Figs. 3(c) and (d) are quasi-coil pipes with $\phi_n=90°$ and 45°, respectively. The angles of combination employed in the experiment are $\phi_2=\phi_3=\cdots=\phi_n=22.5°$ (Fig.3(a)),

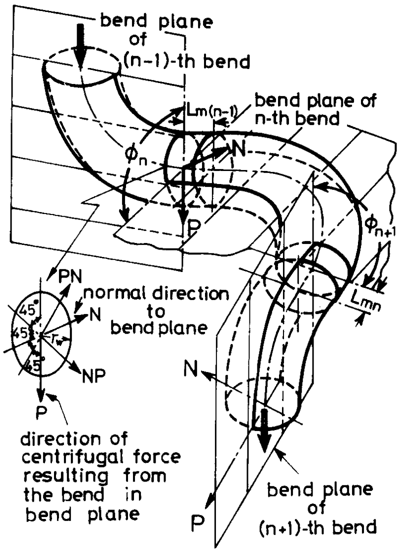
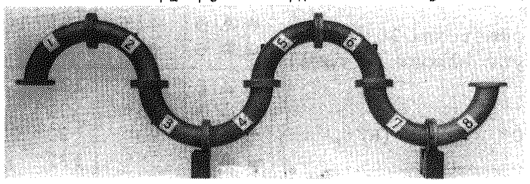
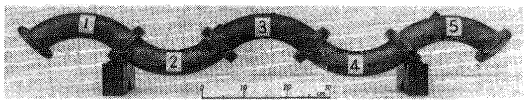


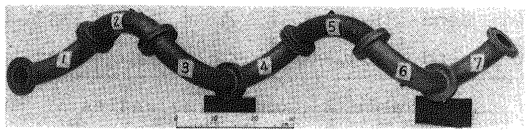
Fig.2 Definition of the connecting angle of bend ϕ_n, the spacer length L_{mn}, and the measuring directions P, NP, N and PN



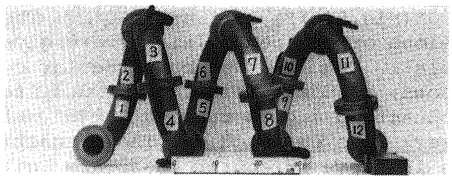
(a) U-shaped wavy bent pipe



(b) S-shaped wavy bent pipe



(c) $\phi_n=90°$ quasi-coil pipe



(d) $\phi_n=22.5°$ quasi-coil pipe

Fig.3 Examples of the wavy bent pipes and the quasi-coil pipes

Table 1 Dimensions of the quasi-coil pipes used in the experiment

		bend elements	R/r_w	connecting angles ϕ_n 22.5°	45°	90°	135°
diameter of quasi-coil pipe D mm		90° elbow	1	—	107	70	51
		90° bend	3	159	142	90	52
		90° bend	6	301	257	159	103
diameter of curvature of quasi-coil pipe D_1 $D_1=D+t^2/\pi^2 D$ mm		90° elbow	1	—	128	126	123
		90° bend	3	169	178	190	211
		90° bend	6	321	329	353	378
length of a turn of coil l_1 mm	appearance $l_{1V}=\sqrt{t^2+(\pi D)^2}$	90° elbow	1	—	369	296	247
		90° bend	3	515	500	411	331
		90° bend	6	976	913	744	618
	$l_{1R}=\Sigma l_m/N$	90° elbow	1	—	325	268	220
		90° bend	3	538	489	401	329
		90° bend	6	984	917	749	609
the number of turns of coil N (n=10)		90° elbow	1	—	2.8	3.3	4.1
		90° bend	3	2.5	2.7	3.3	4.1
		90° bend	6	2.5	2.7	3.3	4.1
pitch of coil t mm		90° elbow	1	—	111	196	190
		90° bend	3	127	225	298	287
		90° bend	6	241	425	552	528
pitch angle θ_0 °		90° elbow	1	—	18	42	50
		90° bend	3	14	27	46	60
		90° bend	6	16	28	48	59
diameter of curvature ratio to pipe diameter D_1/d		90° elbow	1	—	2.4	2.3	2.3
		90° bend	3	3.2	3.4	3.6	4.0
		90° bend	6	6.0	6.2	6.6	7.1

Reference : the connecting angle of wavy bent pipe is $\phi_n=180°$

*1 Every joint between pipes and 90° screw type elbows is fully screwed.

kinds of bend elements	signs	connecting angles								average angles
		ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	
commercial 90° screw type elbows (R/r_w=1)	◐ ◭ ⬖	45°	90°	45°	90°	45°	90°	45°	90°	67.5°
90° bend (R/r_w=3)	◑ ◮ ⬗	90°	45°	90°	45°	90°	45°	90°	45°	
90° bend (R/r_w=6)	◓ ▲ ⬘	45°	45°	90°	90°	45°	45°	90°	90°	
	◒ ▲ ⬙	90°	90°	45°	45°	90°	90°	45°	45°	
	◐ ◭ ⬖	90°	135°	90°	135°	90°	135°	90°	135°	112.5°
	◑ ◮ ⬗	135°	90°	135°	90°	135°	90°	135°	90°	
	◓ ▲ ⬘	90°	90°	135°	135°	90°	90°	135°	135°	
	◒ ▲ ⬙	135°	135°	90°	90°	135°	135°	90°	90°	
	◐ ◭ ⬖	135°	180°	135°	180°	135°	180°	135°	180°	157.5°
	◑ ◮ ⬗	180°	135°	180°	135°	180°	135°	180°	135°	
	◓ ▲ ⬘	135°	135°	180°	180°	135°	135°	180°	180°	
	◒ ▲ ⬙	180°	180°	135°	135°	180°	180°	135°	135°	
commercial 90° screw type elbows (R/r_w=1)	○	135°	180°	180°	180°	157.5°	180°	180°	180°	171.5°
90° bend (R/r_w=3)	△	90°	135°	157.5°	157.5°	202.5°	225°	180°	247.5°	174.4°
90° bend (R/r_w=6)	◇	90°	180°	157.5°	225°	180°	225°	180°	180°	177.2°

Table 2 Connecting angles in the states of irregular combinations of the bend elements

45°, 90°(Fig.3(c)), 135° and 180°. The dimensions of the bend elements are given in Table 1. Besides the above regular combinations, random combinations with different connecting angles ranging in ±45° mutually were also employed. The connecting angles in these irregular cases are given in Table 2. Also, the effects of the spacer length L_{mn} were investigated. The spacer lengths L_{mn} are 0, 1d and 3.5d, respectively. The flow patterns within the bent pipes were measured by means of a cylindrical pitot tube*2. The direction of the measured sections are P, NP, N and PN, respectively, as shown in Fig.2.

4. Equation to predict experimental results

With measured pressures p_1 and p_2, the bend loss coefficient ζ_n[1] in the test length can be calculated by the following relation :

$$H = (p_1 - p_2)/\gamma = \lambda (L/d)(v_m^2/2g) + \zeta_n (v_m^2/2g) \tag{1}$$

, where $L = L_u + \sum_{n=2}^{n} L_{mn} + L_d$, $L_u = 5d$, $L_d = 210d$.

The mutual interference coefficient of bends m is defined by

$$m = \zeta_n / n\zeta_1 \tag{2}$$

The strength of a swirling flow component which is generated in the bent pipes can be calculated by [1]

$$M' = \int_0^{2\pi}\int_0^{1} v_z' v_\alpha' r'^2 dr' d\alpha \tag{3}$$

, where $v_z' = v_z/V_m$, $v_\alpha' = v_\alpha/V_m$, $r' = r/r_w$.

A mean friction coefficient in a bend combination is expressed by

$$\lambda_n = (\zeta_n/n)/(\bar{l}_b/d) \tag{4}$$

($\bar{l}_b$: the center line length of a bend element).

The asymptotic value of friction coefficient in the coiled portion is calculated by[9]

$$\lambda_c = [(\zeta_n - \zeta_{nc})/(n - n_c)] / (\bar{l}_b/d) \tag{5}$$

, where n_c and ζ_{nc} are the number of bend elements and the bend loss coefficients corresponding to the asymptotic values, respectively.

5. Experimental results and discussion

5.1 Hydraulic losses of wavy bent pipes

The relationships between ζ_n/ζ_1 and the number of bend elements n with regard to S-shaped (Fig.3(b)) and U-shaped (Fig. 3(a)) wavy bent pipes are shown in Fig.4. The spacer lengths are L_{mn}= 0, 1d and 3.5d.

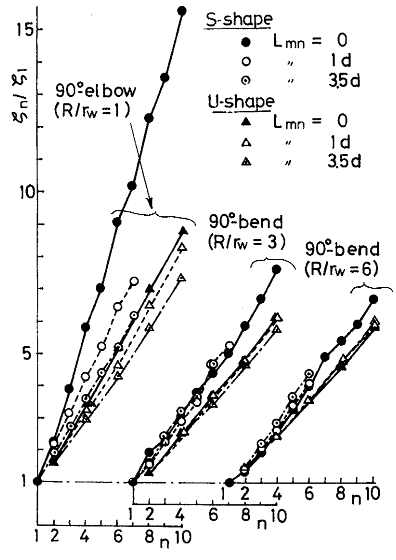


Fig.4 Relations between the bend loss coefficients ζ_n/ζ_1 and the number of the bend elements n in the S- and the U-shaped wavy bent pipes

*2 The rate of flow measured by a pitot tube is about 3～4 % larger than that measured by an orifice.

The value of ζ_n/ζ_1 in S-shaped bends composed of 90° screw type commercial elbows with $R/r_w=1$ is about two times larger than that of ζ_n/ζ_1 in S-shaped bends composed of 90° bends having the ratios of $R/r_w=3$ and 6 when $L_{mn}=0$. But ζ_n/ζ_1 in the elbow combination is nearly the same as that of 90° bends when $L_{mn}\geq 1d$.

The bend loss coefficients in U-shaped wavy bent pipes are generally smaller than those in S-shaped ones, and the effects of the spacer lengths are also smaller. The relationships between the mutual interference coefficients of bends, m, and the number of bends, n, are shown in Fig.5.

The values of m approach asymptotically a constant at about the fifth or sixth bend without regard to the radius of curvature of the bend elements and the spacer lengths.

The asymptotic values of m in S-shaped bent pipes composed of 90° screw elbows are widely variable with the spacer lengths.

This will probably be due to the fact that the scale of the flow separation and the strength of a secondary flow generated in the elbows and downstream are strongly influenced[7] by the inlet velocity profiles. The scale of flow separation in S-shaped wavy bent pipes with $R/r_w=3$ is much smaller than in ones with $R/r_w=1$ (elbows) and the bend loss caused by the flow separation is small. In this case the variations of m are also small. The strength of a secondary flow is sensitive to the spacer length. m takes a minimum at $L_{mn}=0$ and increases monotonously as L_{mn} increases, reaching unity asymptotically.

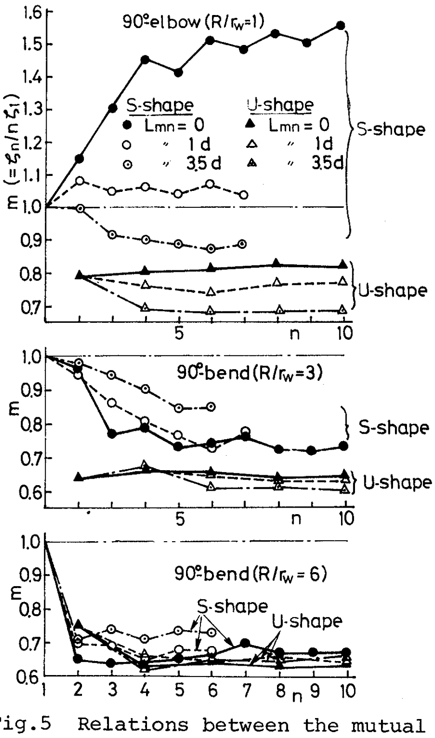


Fig.5 Relations between the mutual interference coefficients m and n in the S- and the U-shaped wavy bent pipes

The variations of m in S-shaped wavy bent pipes with $R/r_w=6$ are smaller than those in ones with $R/r_w=3$. The value of m is nearly equal to 0.65~0.67 at $L_{mn}=0$, and it increases with L_{mn}. This value of $m=0.65$ is nearly equal to that in U-shaped wavy bent pipes as is described below.

If U-shaped bend elements are employed in the bend combinations, the value of m is smaller than unity even in the case of $R/r_w=1$. The effects of the spacer length and the number of bends on m become much less if the bend curvatures of $R/r_w=3$ and 6 are employed in U-shaped wavy bent pipes. The values of m in U-shaped wavy bent pipes with a small bend curvature become smaller than those in S-shaped wavy bend pipes, but the difference becomes less as the bend radius increases. The reason why m in U-shaped wavy bent pipes is smaller than that in S-shaped ones can be explained from the velocity distributions as given in the later Section 5.5.

5.2 Comparison of the loss coefficients in wavy bent pipes and quasi-coil pipes

The experimental results of the loss coefficient ζ_n/ζ_1 are plotted against the number of bends n in Fig.6. The values of S-shaped wavy bent pipes with $\phi_n=180°$ are identified by the symbol ▲. The spacer lengths L_{mn} employed are 0, 1d and 3.5d, respectively. Figure 6(a) shows the results of 90° elbow bend pipes. The curves of ζ_n/ζ_1 have rather irregular tendencies

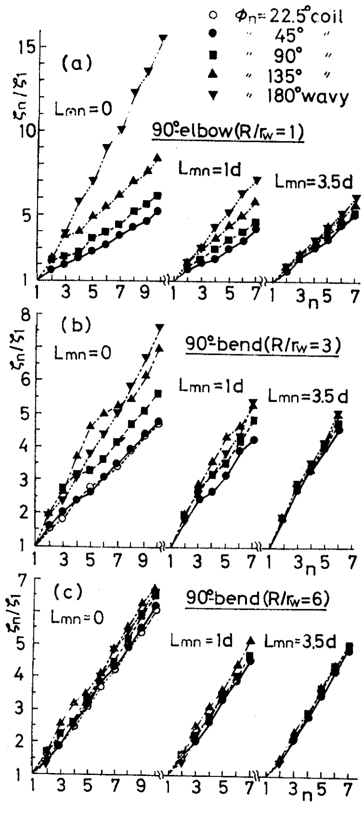


Fig.6 Relations between ζ_n/ζ_1 of the quasi-coil pipes and the S-shaped wavy bent pipes

in the range of $n \leqq 3$, but become regular in the range of $n \geqq 4$ and ζ_n/ζ_1 reaches a maximum at ϕ_n=180°, and decreases as ϕ_n diminishes from 180° to 45°*3. The variations of ζ_n/ζ_1 observed in a change of the connecting angles ϕ_n become less as L_{mn} increases. Figure 6(b) shows the results of R/r_w=3 bent pipes. The ζ_n/ζ_1 curves have complicated tendencies in the range of $n \leqq 4 \sim 5$. But a regular tendency is observed in the range of $n \geqq 8$ as in 90° elbow combinations. The loss coefficient ζ_n/ζ_1 decreases to the minimum value in the range of $\phi_n \leqq 45°$, and ζ_n/ζ_1 in the combinations of ϕ_n=22.5° and ϕ_n=45° shows no substantial difference. Figure 6(c) shows the results of the bent pipes with R/r_w=6. In this case the effect of bend configurations on ζ_n/ζ_1 becomes less than that in the bend combination of R/r_w=3. The loss in wavy bent pipes with ϕ_n=180° is relatively small in the range of $n \leqq 4$ and it increases with n if n is increased beyond the limit. But even in this range ζ_n/ζ_1 does not exceed the loss in the combinations of ϕ_n=135° when $n \geqq 7$. This may be due to the fact that the development of a secondary flow in the curved duct is weakened at the second and the third bends of the wavy bent pipe with R/r_w=6. The losses of the combinations with ϕ_n=135° become relatively large because the development of a one-directional swirling flow is much stronger than that in the other configurations. The loss coefficient ζ_n/ζ_1 in the combination of ϕ_n=22.5° is relatively small and it is approximately equal to that in the combination of ϕ_n=45°. The relationships between m and n are shown in Fig.7. Figure 7(a) shows the results of 90° elbows bend pipes. The variations of m are more complicated in the range of $n \leqq 4$. But m tends to be a constant in the range of $n \geqq 5$ and the value of the constant increases with an increase of the connecting angle ϕ_n. Figure 7(b) shows the results of the bent pipes with R/r_w=3. The variations of m due to ϕ_n are less than those in the case of 90° elbows, and have complicated tendencies in the range of $n \leqq 4$. But the variations become regular and small in the range of $n \geqq 5$, and m increases with an increase of ϕ_n when $n \geqq 8$. Figure 7(c) shows the results of the bent pipes with R/r_w=6. m tends to a constant in the range of $n \geqq 7$. The variations of m are less as compared with those in Figs. 7(a) and (b). Figure 8 shows the asymptotic values of m, which correspond to the values at n =9~10, in Fig.7. The relationships between L_{mn} and the asymptotic values of m are shown in Fig.8(a). The relationships are strongly affected by the curvature ratio of the bends. Especially, the tendencies of 90° elbow bend pipes are extre-

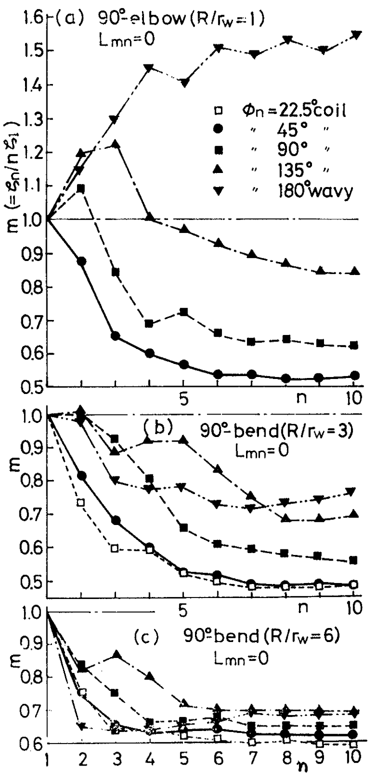


Fig.7 Relations between m of the quasi-coil pipes and the S-shaped wavy bent pipes

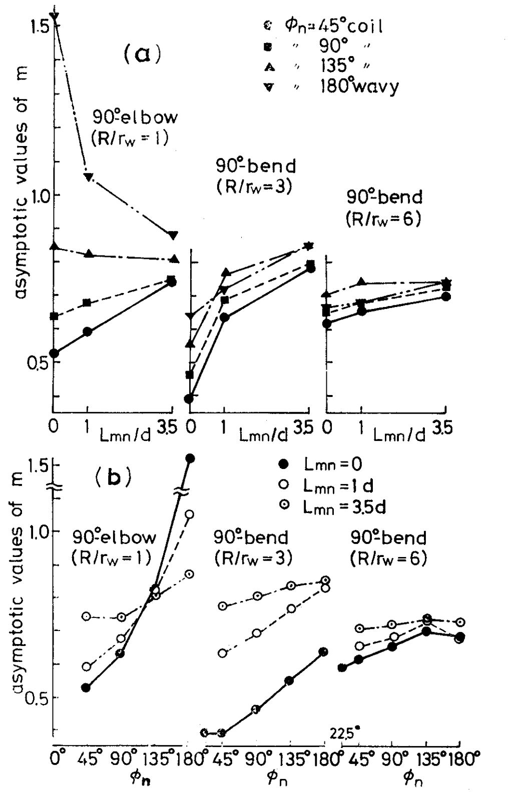


Fig.8 Relations among m, L_{mn} and ϕ_n in the S-shaped wavy bent pipes and the quasi-coil pipes composed of 9 or 10 bend elements

*3 The bends with R/r_w=3 and 6 can be constructed respectively in the range of 22.5°≦ ϕ_n ≦ 180°, but the connecting angles of the R/r_w=1 elbows are limited in the range of 45°≦ ϕ_n ≦ 180° because of the restriction of the bend form.

mely different from those of the bent pipes with R/r_w=3 and 6. Figure 8(b) explains the relationships between the asymptotic values of m and the connecting angles ϕ_n. The values of 90° elbow and of the bent pipes with R/r_w=3 increase with an increasing ϕ_n. The gradients of the increasing ratio are proportional to the curvature ratios of the bends, and are inversely proportional to the spacer length if the curvature ratios of the bends are constant. The bent pipes with R/r_w=6 have a different tendency from the above bend combinations. The values of m in the coil pipes with ϕ_n=135° are a little smaller than those in the wavy bent pipes with ϕ_n=180°.

5.3 The relationships between average connecting angles of bends $\bar{\phi}_n$ and loss coefficient ζ_n/ζ_1

In the above Section the results of the bent pipes with regular combinations

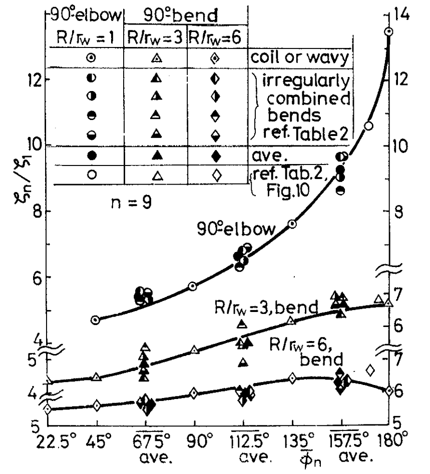


Fig.9 Relations between ζ/ζ_1 in the state of irregular combinations of the bend elements and the average connecting angles $\bar{\phi}_n$

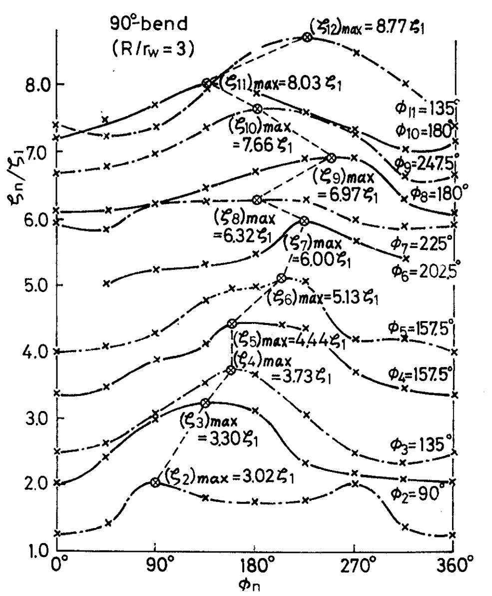


Fig.10 Bend losses in the special combinations of 12 bend elements

have been described. Now, some effects of the irregularity of the bend combinations on ζ_n/ζ_1 will be descrived below.

The relationships between $\bar{\phi}_n$ and ζ_n/ζ_1 are shown in Fig.9. $\bar{\phi}_n$ is an average value of the connecting angle ϕ_n for nine 90° bends. The connecting angles of the bent pipes used in the experiment are listed in Table 2, and the angle of the deviation in mutual bends differs ±45 degrees from the states of the regular combinations. The combination is done such that the third bend is connected to two combined bends which show the largest bend loss in all of two bend combinations. The fourth bend is connected in the same manner. Figure 10 shows the loss coefficients for the twelve bend combinations obtained as above. The solid lines connecting the symbols ⊙, △, ◇ in Fig.9 correspond to the values in the regular bend combinations. The other symbols correspond to those in the irregular combinations cited in Table 2. The relationships between $\bar{\phi}_n$ and ζ_n can be approximated by the solid lines. From these results, the loss coefficient of bent pipes having a little irregular combinations of the bends can be assumed using the average connecting angle $\bar{\phi}_n$.

5.4 Comparison of the loss coefficients in quasi-coil pipes and smoothly coiled pipes

The mean values of friction coefficients λ_n/λ_0 of the coiled portions in the bent pipes are shown in relation to the center line lengths L/d of the coiled portions in Fig.11. The friction coefficient is expressed as the value of, λ_0, the friction coefficient of a straight pipe having the value of 0.023, when the relative roughness is of order of ε/d=0.001. The values of λ_n/λ_0 increase when the curvature ratio of the bends decreases and ϕ_n increases. The values of λ_n/λ_0 are seen

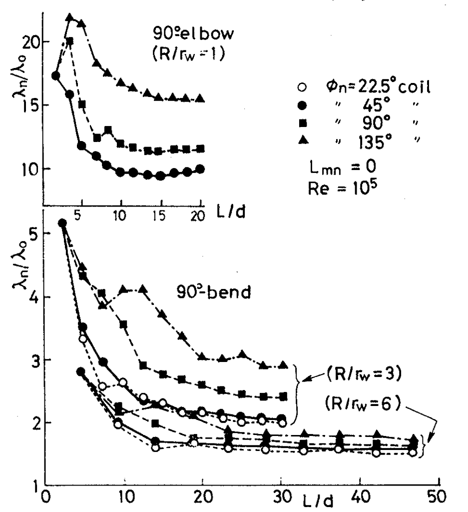


Fig.11 Relations between the mean friction coefficient λ_n/λ_0 of quasi-coil pipe and the center line length of the pipe

to be a little variable in the range of $\phi_n \leqq 45°$. The friction coefficients λ_n in the bent pipes with $R/r_w=6$ have about 1.5 times the value of the straight pipe.
The friction coefficients of the quasi-coil pipes can be compared with the results for smoothly coiled pipes obtained by Ito[(8)] and Murakami et al[(9)] as shown in Fig.12. The abscissa and the ordinate in the figure are $Re(d/D_1)^2$ and $\lambda_c/\lambda_0 (=\lambda_n/\lambda_0)$, respectively. The values of λ_c/λ_0 in the two kinds of coil pipes fairly well coincide if the gross forms of coil pipes are similar, namely, the pitch angle θ_0 and the curvature ratio D_1/d (D_1 : diameter of curvature of coil pipe) are nearly equal. The values marked ▲, △ and +, ● in Fig.12 coincide well with one another. The values of λ_c obtained by Eq.(5) are not just the same with those of λ_c calculated by the equation given in literature (9), but both equations have the same meaning*4.

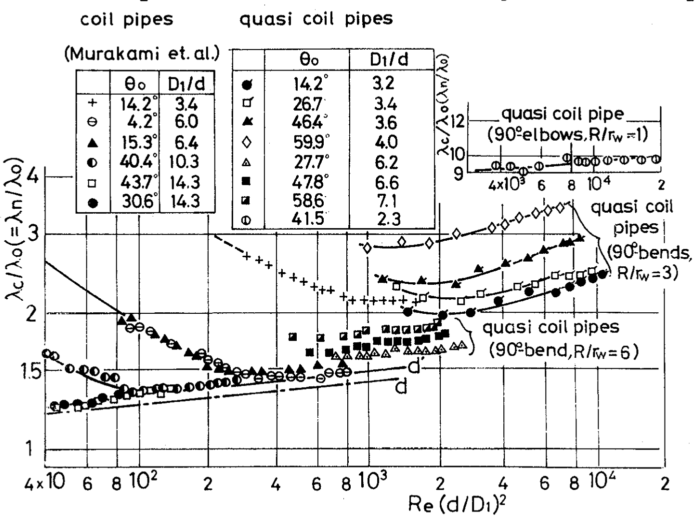


Fig.12 Relations between the friction coefficient λ_c/λ_0 of quasi-coil pipes and smoothly coiled pipes

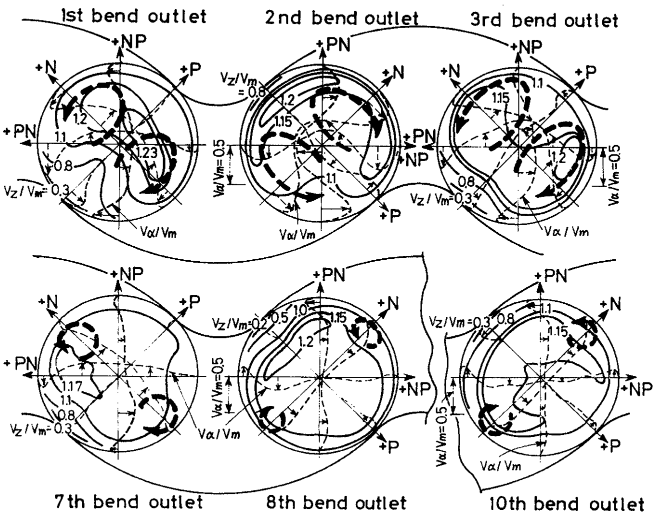
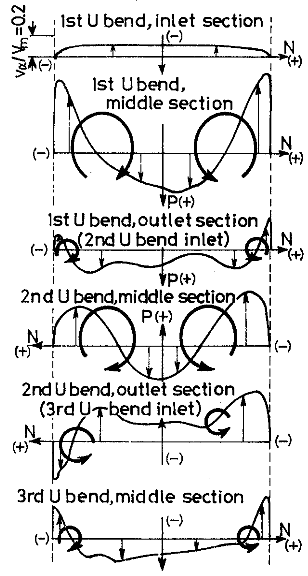


Fig.13 Velocity distributions in the S-shaped wavy bent pipe with $R/r_w=3$.
solid line : equi axial velocity lines
broken line : peripheral velocity lines

5.5 Velocity profiles in the wavy bent pipes and quasi-coil pipes

The velocity distributions at the outlet sections of the 1st, 2nd, 3rd, 7th, 8th and the 10th bends in S-shaped wavy bent pipes with $R/r_w=3$ are given in Fig.13.
The secondary flow of a double spiral type created in the 1st bend is strengthened in the following bends and continues to the 7th bend without changing the swirling direction. But the swirling direction is reversed in the 8th bend and again the swirling motion of the same direction is maintained in the following several bends.
The strength of this secondary flow is greater than that of one created in a smoothly coiled pipe[(9)]. Moreover, the resulting secondary flow renders uniform the axial velocities in the wavy bent pipe.
Figure 14 shows the peripheral velocity distributions on the N-axis (ref. Fig.2) in the wavy bent pipe with U bends. The secondary flow created in the inlet portion of the 1st U bend has a maximum strength in the middle section of the 1st U bend and again is weakened in the outlet section of the 1st U bend*5.



U-shaped wavy bend ($R/r_w=3$)

Fig.14 Peripheral velocities on the N axis (Fig.2) in U-shaped wavy bent pipe with $R/r_w=3$

*4 The number of turns in the coil is about 2.5~4 and is not enough to rigorously calculate λ_c. Accordingly, it is assumed that λ_n approximates to λ_c in nine bends, and this value λ_n is used instead of λ_c. In Eq.(5)., a single 90°-bend corresponds to the unit turn in the smoothly coil pipe[(9)].

*5 The developing and decaying processes of the secondary flow in the U bends are already explained in the literature (1), (7).

As the secondary flow created in the 1st bend reaches the inlet portion of the 2nd U bend, the development of newly generated vortices is delayed and the maximum value is attained near the outlet section of the 2nd U bend. The vortices are weakened in the 3rd U bend. In this case a continuous development of the secondary flow as seen in S-shaped wavy bent pipe does not occur, and the strong and weak vortices are created repeatedly in the following U bends. As the result, the value of m in a U-shaped bent pipe is smaller than that of an S-shaped one and such changes of flow patterns are not altered by the curvature ratio of the bend elements. The values of m in both kinds of bent pipes are about the same as shown in Fig.5, because the vortices created in the S- and U-shaped bent pipes with $R/r_w=6$ are weak enough. But the values of m in the S- and U-shaped bent pipes with $R/r_w=1$ are considerably different because the strengths of vortices in both kinds of bent pipes are different. The strengths of the swirling flow M'(Eq.(3)) in the quasi-coil pipes with $R/r_w=3$ are shown in Fig.15. The swirling motion develops from the 1st bend and M' reaches a constant value in the 5th or 6th bend. This constant value of M' increases with an increasing ϕ_n in the range of $n \geq 6$ and $\phi_n \leq 135°$. The relationships between M'(ref. Fig.15) and ζ_n/ζ_1 (ref. Fig.6(b)) in the 10th bend are shown in Fig.16. The loss coefficient ζ_n/ζ_1 increases with an increase of M'. These tendencies remain the same even if the curvature ratio of the bend is changed, but the value of M' increases as the curvature ratio diminishes.

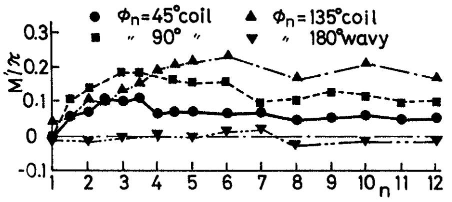


Fig.15 Strengths of uni-directional swirling flow, M', in quasi-coil pipes, $R/r_w=3$. (the values obtained at the inlet of the n th bend)

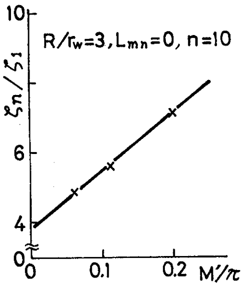


Fig.16 Relations between ζ_n/ζ_1 and M' in the quasi-coil pipe with $R/r_w=3$ at $L_{mn}=0$, $n=10$

6. Conclusions

The hydraulic losses and the flow patterns in the wavy and the quasi-coil bent pipes were examined experimentally. The results obtained can be summarized as follows.

(1) The hydraulic losses in the quasi-coil pipes composed of 90° bends and 90° screw type elbows, increase as the connecting angle ϕ_n and the coil pitch increase.

The maximum hydraulic losses are attained in the wavy bent pipes of $\phi_n=180°$, and the minimum ones in the quasi-coil pipes having small coil pitches when $\phi_n \leq 45°$.

The hydraulic losses in the quasi-coil pipes can be assumed from the results of smoothly coiled pipes if the curvature ratio R/r_w is larger than 3.

(2) Uni-directional swirling flow is created in the quasi-coil pipes and the hydraulic loss in this case is proportional to the swirling strength.

(3) Both the hydraulic loss and the secondary flow in the S-shaped wavy bent pipes having the curvature ratio R/r_w smaller than 3 are larger than those in the U-shaped ones.

(4) The hydraulic losses in the wavy bent pipes become larger than those in the quasi-coil pipes. But the wavy bent pipes are more suitable for heat exchanger ducts than the quasi-coil pipes, since the mixing in flow is more vigorous in the wavy bent pipes.

The S-shaped wavy bent pipe with $R/r_w=3$ is considered to be most suitable for the heat exchanger, because the hydraulic loss is relatively small and the secondary flow is stronger than the one in the other bent pipes.

(5) The hydraulic losses in the bent pipes having a little irregular combinations can be estimated within an error of 5~6 % from the data on the bent pipes of regular combinations if the deviation of angle irregularity is less than ±45°.

References

(1) Murakami,M. and Shimizu,Y., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.43, No.365(1977-1), p.174.

(2) Rowe,M., J. Fluid Mech., Vol.43, Part 4(1970), p.771.

(3) Руденко,И.И., Проблемы Теплоэнергетики и Прикладной Теплофизики, Вы п.6 (1970), 133.

(4) Murata,S., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.42, No.353(1976-1), p.197.

(5) Murata, S. and Inaba,O., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 43, No.373(1977-9), p.3291.

(6) Yamashita,H., et al., Preprints of The Japan Soc. Mech. Engrs. (in Japanese), Kansai-shibu, No.240(1979-11), p.60.

(7) Murakami,M., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.35, No.272(1969-12), p.1369.

(8) Ito,H., Mem. Inst. High Speed Mech., Tohoku Univ. (in Japanese), Vol.14, No.137(1959), p.137.

(9) Murakami,M., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.37, No.296(1971-4), p.717.