Bulletin of JSME, Vol. 28, No. 241, July 1985

Paper No. 241—7

Flow Patterns and Hydraulic Losses in Quasi-coil Pipes*
(The effects of configuration of bend cross section, curvature ratio and bend angle)

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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. In the present paper, one of the pipes with bend combinations, namely, quasi-coiled pipes composed of many bend elements are investigated, and the relationships between the hydraulic loss and the secondary flow are studied experimentally. The configurations of the cross sections, the bent angles and the curvature ratios of the bend elements of the quasi-coiled pipes are changed in the experiment. The effects of these factors are investigated in detail.

As the result, it is found that the secondary flow becomes the type of a one-directional swirling flow in the quasi-coiled pipes if the bend cross sections are changed from circular to rectangular. Moreover, many interesting results are described.

Key Words : Turbulence, Quasi-coiled Pipe, Hydraulic Loss, Secondary Flow, Curvature Ratio, Circular Section, Square Section, Rectangular Section, Aspect Ratio

1. Introduction

Coiled pipe is useful as a heat exchanger because of a strong secondary flow caused in it and its mixing effect. The authors proposed, in the former report(1), several types of coiled pipes formed by connecting many 90° bends together in turn, and made clear that a special secondary flow and its active mixing action occur in such a bent pipe.

In this report, the authors investigated experimentally the effects of the shape of section, ratio of the radius of curvature and bent angle on the flow conditions in each element of the pipe. Also, they studied the relations between the state of flow and hydraulic losses in these pipelines.

Results reveal interesting facts which differ from those obtained by the former experiments with 90° bend quasi-coiled pipes.

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2. Nomenclature

- b, h : lengths of both sides of a rectangular section bend (Fig.1)
- d : hydraulic diameter, $=2r_w$ (r_w: equivalent radius)
- D : apparent diameter of quasi-coiled pipe (reference 1, table 1)
- D_l : diameter of curvature of quasi-coiled pipe, $=D+t^2/\pi^2 D$
- g : acceleration of gravity
- L : total length of straight sections on pipeline, $=L_u+L_d$
- p_u, p_d, p_{w0}: wall pressures at upper stream $L_u=5d$, down stream $L_d=(60\sim210)d$ and just behind of exit of the bend, respectively
- R : radius of curvature of the bend
- v_m : mean axial velocity measured by pipe orifice
- v_z, v_θ : axial and peripheral components of velocity
- λ : coefficient of hydraulic friction of the straight pipe
- ρ : density
- β_0 : bent angle of the element

Suffixes

- c : asymptotic value which approaches an almost steady state
- n : number of bend elements

3. Equations to Predict Experimental Results

In order to discuss the results obtained, we use the following definitions. The bend loss coefficient : ζ_n

$$(p_u-p_d)/\rho g=[\lambda(L/d)+\zeta_n](v_m^2/2g) \quad \cdots(1)$$

The mutual interference coefficient of bends : m

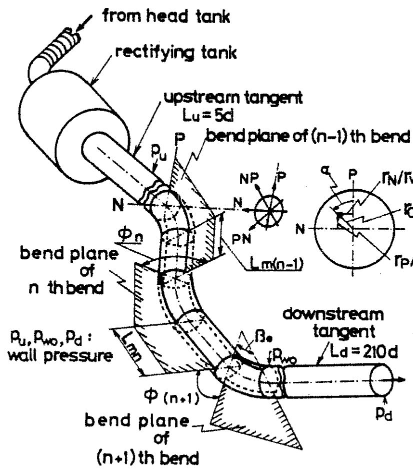
$$m=\zeta_n/n\zeta_1 \quad \cdots\cdots(2)$$

Non-dimensional angular momentum flux which denotes a one-directional swirling flow produced in the bend : M'

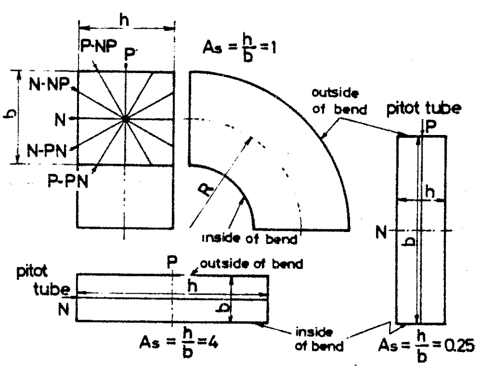
$$M'=\frac{1}{\pi}\int_0^{2\pi}\int_0^1 (v_z/v_m)(v_\theta/v_m) \times (r/r_w)^2 d(r/r_w)d\theta \quad \cdots\cdots(3)$$

4. Experimental Apparatus and Procedures

Figure 1 shows an outline of the experimental apparatus with connecting angle of the elements and measuring directions of velocity in a cross section of the element. Flow enters the first bent section through the rectifying tank and a sufficiently long inlet. One pressure tap is fixed at $L_u=5d$ upstream tangent and several ones at downstream tangent, respectively. The last pressure taps are situated at $210d$, $100d$ and $60d$ downstream of the last bend in the case of a circular pipe, a square pipe and a rectangular pipe, respectively.



(a) Schematic diagram of experimental apparatus and definition of connecting angle of bends ϕ_n



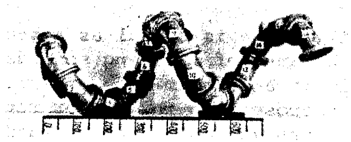
(b) Definitions of aspect ratio A_s of rectangular section of bend and the measuring directions P, P·NP, N·NP,····

Fig.1

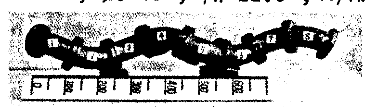
Shape of section, bent angle and curvature ratio of the element used in this experiment are shown in Table 1. The results for circular bent pipes with β_o=90° published in former report[1] are quoted in this report. Sixteen 45°-bends and five 180°-bends are connected at the most. Connecting angle ϕ_n is taken plus counter-clockwise (Fig.1(a)). Two states of a regular connection of $\phi_1=\phi_2=\cdots=\phi_n$, say, quasi-coiled pipe, and an irregular connection of which angle shifts by forty-five degrees from each other were investigated.

In case of square or rectangular section, a quasi-coiled pipe of ϕ_n=90° and a wavy pipe of ϕ_n=180° were adopted, but the latter will be considered separately in reference (3) owing to many things to be discussed. Aspect ratios of rectangular sections were two, i. e., A_s=0.24 and 4, and maximum number of them used in pipeline was 6～12. And, two types of pipelines A and B were proposed, i. e., the A type having a bend of A_s=4 at the first and A_s=0.24 at an even numbered position, and the B type which reverses the order in the former. In this experiment, the pipeline had no straight parts between any bends.

Figure 2 shows representative examples of quasi-coiled pipes tested. Main dimensions of these pipes are tabulated in Table 1. Velocity distributions in several traverse directions such as P, N, NP etc. in the outlet section of the n-th bend shown in Fig.1 were measured with the

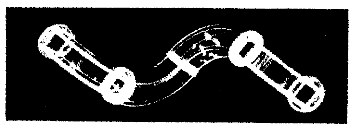


circular, β_o=45°, ϕ_n=22.5°, R/r_w=6

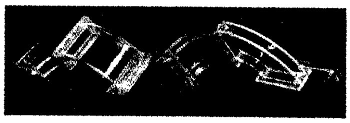


circular, β_o=45°, ϕ_n=90°, R/r_w=6

circular, β_o=180°, ϕ_n=22.5°, R/r_w=6



square, β_o=90°, ϕ_n=90°, R/r_w=6



rectangular, β_o=90°, ϕ_n=90°, R/r_w=6

Fig.2 Examples of test quasi-coiled pipes aid of a three hole pitot-tube, excluding only one direction in rectangular section bend.

Experiments were carried out at the Reynolds number of $v_m d/\nu = 10^5$ since the results were not influenced by the Reynolds number more than 10^5 as reported before[1][4].

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

shape of section radius ratio of curvature bent angle of element	connecting angle ϕ_n °	pitch angle θ_0 °	diameter ratio of curvature to pipe diameter D_1/d
circular 2 45°	22.5	34	2.4
	45	46	2.8
	90	53	2.6
	135	73	3.5
circular 3 45°	22.5	28	3.1
	45	44	3.1
	90	64	3.0
	135	77	5.4
circular 6 45°	22.5	26	6.0
	45	45	6.3
	90	65	6.6
	135	76	9.0
circular 1 180°	60	19	2.2
	90	28	2.3
	135	40	2.5
circular 3 180°	45	24	3.3
	90	28	3.5
	135	40	4.4
circular 6 180°	22.5	7	6.1
	45	14	6.2
	90	29	6.5
	135	40	7.2
square, rectangular 6 90°	90	47	6.6

circular : d =53.4 mm ϕ, 45°-bend : smooth wall
90°-bend : rough wall, relative roughness 10^{-3}

rectangular : hydraulic diameter d =52.6 mm , smooth wall

D_1 ($=D + t^2/\pi^2 D$) : diameter of curvature of quasi-coiled pipe

5. Experimental Results

5.1 States of flow in the quasi-coiled pipes with various sectional forms

5.1.1 Circular section

Typical examples of velocity distributions in pipes coiled with ϕ_n=22.5° and 90° with circular bends of β_0=45°, R/r_w=6 are illustrated in Fig.3 and Fig.4. In Fig.3, ϕ_n=22.5°, a couple of symmetrical secondary swirls occurs in the 1st bend outlet, but, after the 2nd bend, this symmetry is lost, transforming into a couple of large and small swirls. A couple of asymmetrical swirls last as far as the 16th bend without disappearance.

On the other hand, in Fig.4, ϕ_n=90°, a one-directional large swirling flow swaying the whole section appears, and it is so intensive that it has 0.5 times the mean axial velocity at maximum. As the result, loss of bend and degree of interference of the bends increase. Figure 5 shows velocity distributions in the outlet sections from the 1st to the 8th bend of a wavy pipe of ϕ_n=180°. Velocity distributions are so symmetrical to the P-axis that they are illustrated only for half of the left in Fig.5. Swirling components are considerably smaller than those of ϕ_n=90°.

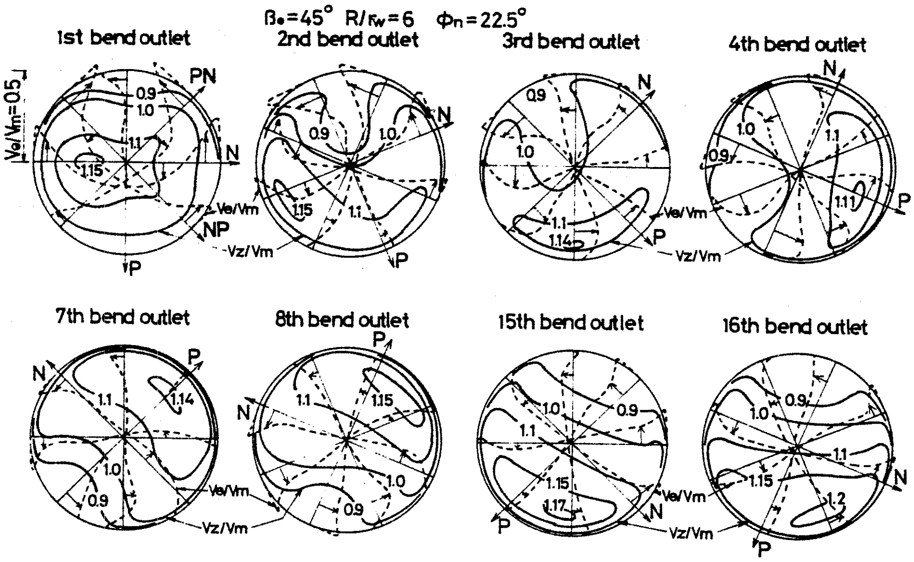


Fig.3 Velocity distributions in ϕ_n=22.5° quasi-coiled pipe
(β_0=45°-bends with circular section used)
——— : equi-axial velocity line
----- : peripheral velocity distributions

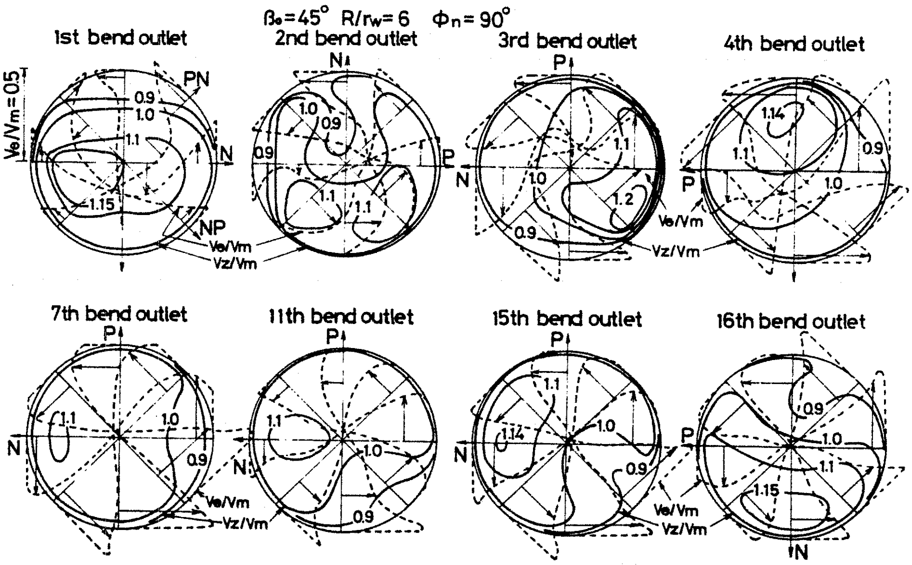


Fig.4 Velocity distributions in ϕ_n=90° quasi-coiled pipe
(β_0=90°-bends with circular section used)
——— : equi-axial velocity line
----- : peripheral velocity distributions

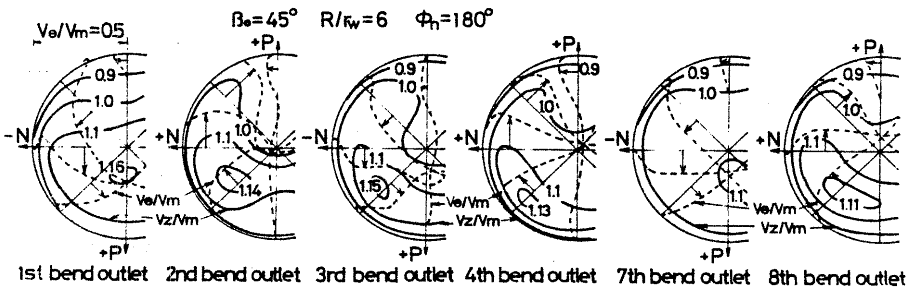


Fig.5 Velocity distributions in wavy bent pipe (ϕ_n=180°)
(β_0=45°-bends with circular section used)
——— : equi-axial velocity line
----- : peripheral velocity distributions

In Fig.6, non-dimensional angular moment flux M' measured in the quasi-coiled pipe which is made with 45° bend of R/r_w = 3 or 6 at different connecting angles is shown against number of bends. A one-directional swirling flow develops, at first, from the 1st to n=(5∼10)th, and then, after the maximum value, settles a constant at farther connections. Maximum value of this swirling flow M'≒0.4 is reached at R/r_w=3, ϕ_n=90°. This is larger than that obtained from 90° bends(1). On the whole, an intense swirling component appears at small curvature ratio. The relation between M' and n corresponds well to that of bend loss described by ζ_n/ζ_1 in § 5.2. This may be explained from the transformation of the pressure into the kinetic energy when a secondary flow occurs through mutual interference of bends.

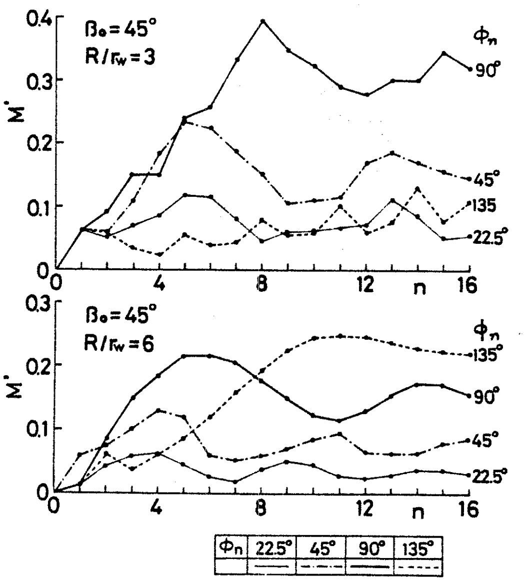


Fig.6 Relations between number of bends n and strength of one-directional swirling flow M' occurring in quasi-coiled pipes. β_0=45°-bends with circular section used. R/r_w=3, 6. ϕ_n changed

Figure 7 shows the non-dimensional angular momentum flux M'_{nc} at the position in which the swirling flow develops to the extent of approximate constant condition. Generally, M'_{nc} shows large values at small curvature ratio and small bent angle. For the same connecting angle ϕ_n, M'_{nc} decreases in order of β_0=45°, 90°, 180°. From the results and Table 1, it can be said

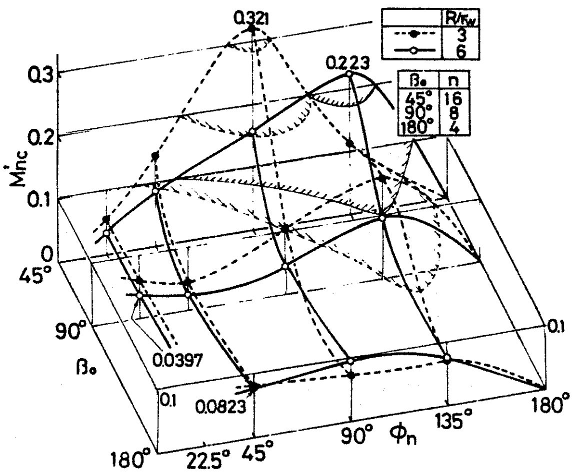


Fig.7 Relations among strength of one-directional swirling flow M'_{nc} (asymptotic values) in quasi-coiled pipes, bend angle β_0 and connecting angle ϕ_n

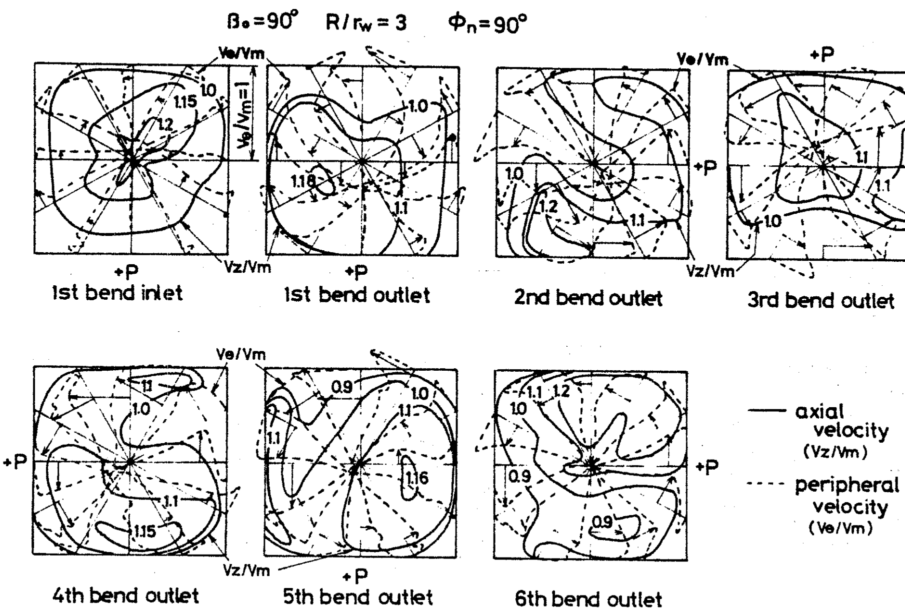


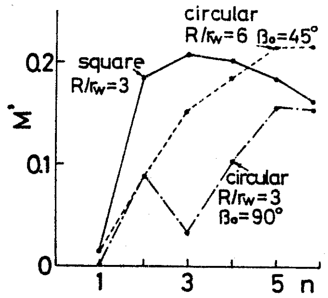
Fig.8 Velocity distributions in quasi-coiled pipe (β_0=90°-bends with square section used)

that a swirling flow appears more intensely when the pipe is coiled at small apparent diameter with large pitch angle than a reverse one.

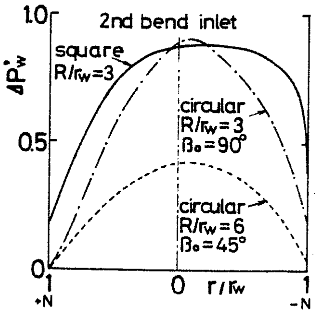
5.1.2 Square or rectangular section

Figure 8 shows the velocity distributions in a square quasi-coiled pipe made with β_o=90°, R/r_w=3 and ϕ_n=90°. Symmetrical secondary flow is produced in the 1st bend, and a part of high velocity enters the 2nd bend. After that, the one-directional swirling flow is continued.

Several values of M' in the square and the circular coiled pipes calculated from the velocity distributions are compared in Fig.9(a). From the figure, we can see a considerable difference between square and circular before and after both of the results approach each other at n = 5～6. Remarkable development of a swirling flow in a square bend will be explained from the asymmetry of pressure difference on the inside and the outside walls due to the centrifugal force as shown in Fig.9(b). The development of a one-directional swirling flow is not so rapid in circular section.



(a) Strength of one-directional swirling flow in quasi-coiled pipe
——— : β_o=90°-bends with square section, R/r_w=3
----- : β_o=45°-bends with circular section, R/r_w=6
—·—·—: β_o=90°-bends with circular section, R/r_w=3



(b) Distributions of pressure differences between inside and outside walls near inlet of 2nd bend

Fig.9

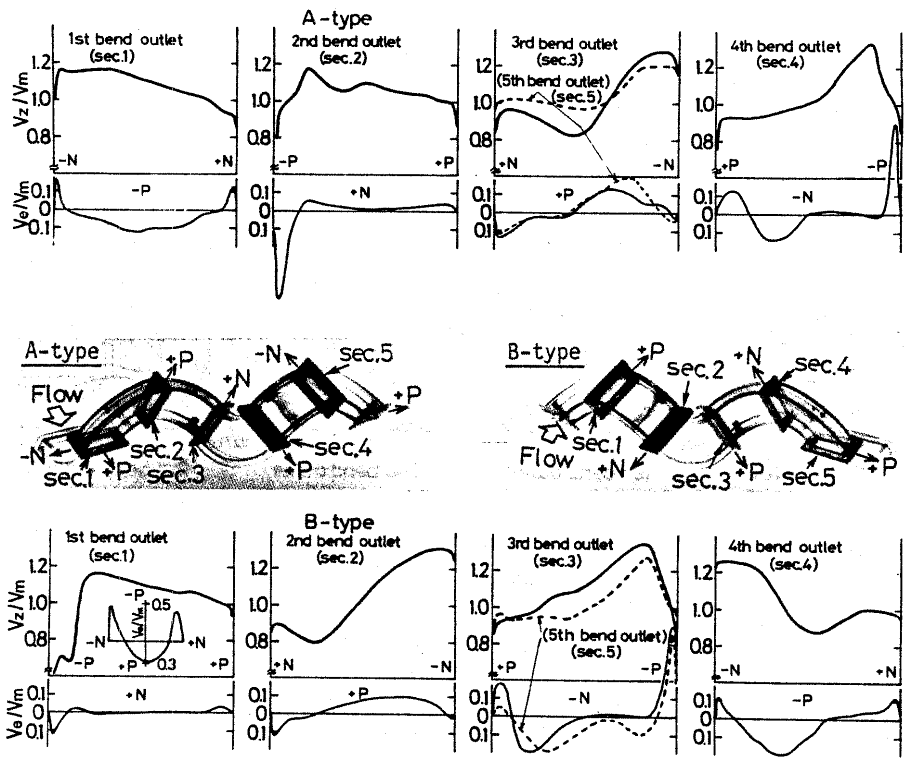


Fig.10 Velocity distributions in quasi-coiled pipe (β_o=90°-bends with rectangular section used). upper side : A shape, lower side : B shape, measured values along longitudinal direction

Figure 10 shows the velocity distributions in rectangular quasi-coiled pipes measured along longitudinal side of the section. The upper figures correspond to the A-type pipe and the lower ones to the B-type. With regard to the A-type, we can see that a weak symmetrical secondary flow in the 1st bend outlet turns into a strong secondary flow in the 2nd and 3rd bends, and after passing through the 4th bend, velocity distributions in the 5th bend outlet take nearly the same form as shown by broken lines in the 3rd bend again. From this observation, it is supposed that, in case of the A-type pipe, the flow pattern in the 3rd and 4th bends will be repeated after 5th and 6th bends. About the B-type coiled pipe, velocity distributions in the 5th bend agree well with ones in the 3rd bend though the progress of the flow patterns is somewhat different from the A-type, so it is supposed that the flow repetition will be caused after the 5th bend, too.
In either case, a couple of symmetrical secondary swirls occur in the 1st bend, and after the 2nd bend, they turn into a asymmetrical secondary flow accompanied with a couple of weak and strong contrary swirling components.

5.2 Hydraulic losses in quasi-coiled pipes
5.2.1 Circular section

In this paragraph, we investigate the hydraulic losses caused in these coiled pipes having different sections. Figure 11 shows the coefficients of bend loss and mutual interference against the number of bends of R/r_w=6, β_o=45°. Maximum values of ζ_n/ζ_1 are obtained for ϕ_n=135°, and the minimum ones for 180°. The latter fact results from the weak secondary flow shown in Fig.5. In case of a wavy pipe of 90° bends quite opposite results to the case of 45° bends have been obtained[(1)]. This is worthy of attention.

About the coefficient of interference, as shown by broken lines, it reaches a constant at n=10~12 for ϕ_n=90° coiled pipes which have a large hydraulic loss, and at comparatively small number for ϕ_n=180° pipeline with a small loss of head. These differences described above are based on the internal flow pattern, in particular, the intensity of the one-directional swirling flow (Fig.6).

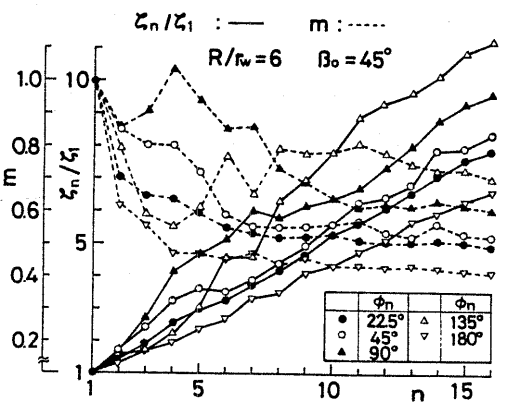


Fig.11 Relations among coefficients of non-dimensional bend loss ζ_n/ζ_1 and mutual interference m and number of β_o=45°-bends n

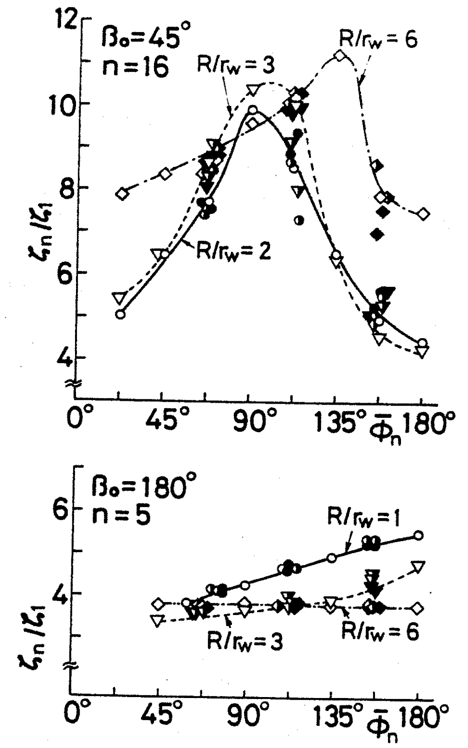


Fig.12 Comparison of non-dimensional bend loss coefficients ζ_n/ζ_1 of regular and irregular connections of bends. $\bar{\Phi}_n$ expresses mean values of connecting angle. See Table 2 in Ref.(1)
○ , ▽ , ◇ signs : $\phi_{n-1}=\phi_n=\phi_{n+1}=\cdots\cdots$, regular connection
◑ , ▼ , ◈ : irregular connection of single bends is due to shifting of the connecting angle by 45°
● , ▼ , ◆ : irregular connection of a couple of bends is due to shifting of the connecting angle by 45°

5.2.2 Loss of bend in quasi-coiled pipes with circular section of regular or irregular connection as the coefficient of interference becomes steady

As shown in Fig.11, the coefficient of hydraulic loss increases linearly after the interference coefficient reaches the steady state. Typical examples of such case are illustrated in Fig.12 about the regular or irregular connection of bends. Irregular connections are due to a shifting of the connecting angle by 45°. $\bar{\phi}_n$, abscissa, is mean value of connecting angle.

5.2.3 Square or rectangular section

Relations between coefficient of bend loss or mutual interference and the number of bends in both cases of circular and rectangular sections are shown in Fig.13(a),(b). Losses due to a bend pipe with a square section agree with those with circular section with a little difference so far as n=6, suggesting that the coefficient of interference m will approach the constant at n= 10 as in case of a circular section reported before[1]. Rectangular section coiled pipes are divided into two types of A and B (Fig.10), and are made with bends of As=4 and 2.5 joined together. Results of rectangular case show a considerable difference in values of the coefficients from those of circular or square section in both types. The former values become larger than those of the following two sections.

Figure 14 shows the bend loss coefficients calculated from eq.(1), in regard to single bends of 45° or 90° with circular, square or rectangular section. Results by Smith[5] are added as reference. They agree with author's ones.

6. Conclusions

(1) Secondary flow of a one-directional swirl or asymmetrical one with a couple of weak and strong swirling components appears in a coiled pipe regardless of its section circular, square or rectangular. Swirl becomes strong at small apparent coil diameter and large pitch, but weak at large coil diameter and small pitch.

(2) In a quasi-coiled pipe of square section with small curvature ratio, a one-directional swirl develops rapidly and, in some cases, exceeds the case of circular section. In case of rectangular section bends, it is expected that a couple of bends of different aspect ratios produce a repeated flow of similar pattern after the 3rd bend.

(3) Symmetrical secondary flow caused in a wavy pipe of circular section becomes most intense in 90° bend, and weakened in 45° or 180°.

(4) Hydraulic loss coefficients of a quasi-coiled pipe with circular or rectangular section were calculated and illustrated.

References

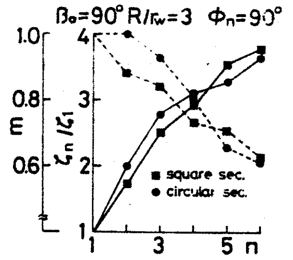
(1) Shimizu, Y., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), 47-417 (1982), 762.

(2) Murakami, M. and Shimizu, Y., Trans. Japan Soc. Mech. Engrs. (in Japanese), 35-272 (1970), 763.

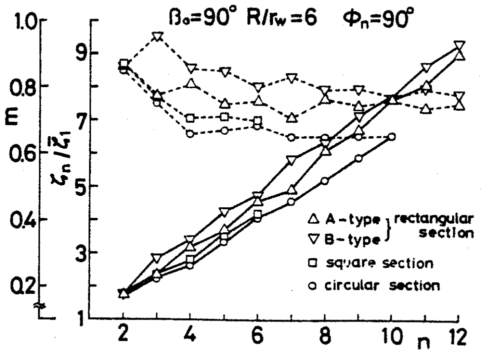
(3) Shimizu, Y., et al., Preprints of Japan Soc. Mech. Engrs. (in Japanese), No.820 -14 (1982), 277.

(4) Shimizu, Y. and Murakami, M., Trans. Japan Soc. Mech. Engrs. (in Japanese), 43-365 (1977), 174.

(5) Smith, A. J., Butterworth, Pressure losses in ducted flows, (1971), 56.



(a) Comparison of non-dimensional bend loss coefficients with mutual interference coefficients in quasi-coiled pipes with square and circular sections



(b) Relations among number of bends n and non-dimensional bend loss coefficients ζ_n/ζ_1 and mutual interference coefficients m of quasi-coiled pipe with rectangular section

Fig.13

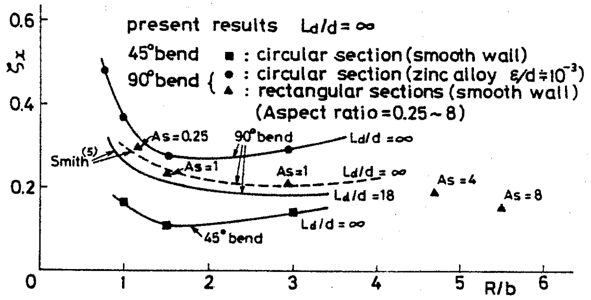


Fig.14 Comparison of bend loss coefficients of β_0=45° and β_0=90° single bends (bend sections are circular, square and rectangular)