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An experimental investigation of the frictional pressure drop of steam–water two-phase flow in helical coils

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Abstract

Fractional pressure drops of single-phase water and steam–water two-phase flows were studied in a pressure range of 3.0–3.5 Mpa. Two helical coiled tubes were employed as test sections and their four different helix axial inclinations were examined. It is found that helix axial angles have little influence on the single-phase frictional pressure drop, while variation of the steam–water two-phase flow frictional pressure drop is enlarged to 70%. For single-phase flow, some previous correlations were quite accurate in predicting the frictional pressure drop for lower Reynolds number conditions, and a modified correlation was obtained from an enlarged Reynolds number range of the present test. For boiling two-phase flow, great deviation was found among the published few empirical equations and their capability of practical utilization is rather poor on account of their complication in structure. A new easily stipulated correlation is deducted from our present data. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Steam–water two-phase flow; Frictional pressure drop; Helical coiled tubes

1. Introduction

Helical coiled tubes are of special interest for their many practical advantages, such as compactness, easy manufacture and high efficiency in heat transfer. They have been widely used for compact heat exchanges in boilers, equipment of the chemical industry and even in military areas [1,2]. Also, helical coiled tube has been recommended as one of the passive heat transfer enhancement techniques by Prof. A.E. Bergles, the 1995 Jakob award recipient.

During the designing and operating processes of helical coiled tubing steam generators, the prediction of pressure drop of single-phase flow and two-phase mixtures is an essential step for the adjustment of pump pressure head and even calculation of heat transfer conditions. Despite considerable progress that has been made in the past several decades this, and many different correlations (such as that of Berger and Talbot [3], Akagawa et al [4], Chen and Zhou [5], Unal et al. [6], Nariai et al. [7], Watanabe et al. [8], Guo et al. [9]), were proposed. It is far from satisfaction, especially for convective boiling two-phase flow conditions. For single-phase flow, a literature survey indicates that the presently employed correlations are commonly obtained in a rather lower Reynolds number region, none of them exceed the range of $Re > 1.5 \times 10^5$. Of course, it should be addressed that some early published correlations as that of Ito's [10] and Srinivasan et al.'s [11] perform with an excellent accuracy when used in the lower Reynolds number regions of $Re < 1.5 \times 10^5$. But, we are not sure what they are capable of in the higher Reynolds number region. For boiling two-phase flow, among the limited investigations, most of them were conducted in vertical coils and only a few [8,9,12] related to horizontal coils. However, those measured with either vertical or horizontal coils are carried out in one helix axial direction. The exchanging possibility among these obtained correlations is limited by not knowing how much the helix

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Nomenclature

d	tube inner diameter (m)
f	frictional factor (non-dimensional)
n	coil circle numbers
Δ	pressure (Pa)
q	tube inner heat flux (kW/m^2)
u	mass velocity (m/s)
X_{tt}	Martinelli parameter
D	coil diameter (m)
G	mass flow rate (kg/m^2 s)
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
x	averaged mass quality

Greek symbols

α	void fraction of tube outlet
μ	dynamic viscosity (kg/m s)
Φ^2_{lo}	two-phase multiplier
ρ	density (kg/m^3)
ξ	coefficient (Eq. (5))

Subscripts

tp	two-phase
cr	critical
l	liquid phase
c	coil
g	steam phase
w	tube wall

axial directions influence the two-phase flow frictional pressure drop values. Especially, heat exchanger positions are frequently oriented in those of underwater navigation and space flights [13,14] and the effect angle of gravity is varied among them. The behavior of single- and two-phase flows in such a coil is expected to be different from that of flow in vertically or horizontally positioned coils. This difference may be pronounced when the centrifugal force is less than or equal to the gravity force and therefore the frictional pressure drop may differ as well. On the other hand, gravity influences the distribution of the secondary flow which is developed along the circumference direction of the coiled tube and is considered as one of the major variations which increases the frictional pressure drop compared to the same straight tube [4].

In the following discussion, a summary of the published correlations of frictional pressure drop in helical coils, including laminar flow, turbulent flow, transition between laminar and turbulent flows, and boiling two-phase flow frictional pressure drops, is drawn to provide a better understanding of the present research in this area.

2. Summary of the previous researchers

2.1. Single-phase flow

2.1.1. Laminar flow region

Due to its unpopular utilization, the laminar flow frictional pressure drop in helical coils and curved pipes is rarely researched. White proposes a commonly used correlation in early 1929 (see [4])

$$\frac{f_c}{f_s} = 0.25 \Bigg/ \left\{ 1 - \left[1 - \left[\frac{11.6}{Re(d/D)^{0.5}} \right]^{0.45} \right]^{1/0.45} \right\}, \qquad (1)$$

where f_c is the friction factor of the curved pipe, and f_s is the friction factor for the straight tube.

$$f_s = \frac{64}{Re}. \qquad (2)$$

Later, Ito [10] suggested another correlation as

$$\frac{f_c}{f_s} = 86K/(1.56 + \log K)^{5.7}, \qquad (3)$$

where $K = Re(d/D)^{0.5}$ and is named as the Dean number in helical coiled tube researches. The friction factor calculated from Ito's equation is a little lower than for White's correlation.

Schmidt [15] also suggested a correlation for the laminar region in curved pipes as

$$\frac{f_c}{f_s} = \left[1 + 0.14 \left(\frac{d}{D} \right)^{0.97} Re \right]^i \qquad (4)$$

where $i = 1 - 0.644(d/D)^{0.312}$. This equation closely agrees with White's correlation.

Akagawa et al. [4] and Watanabe et al. [8] also conducted an experimental research of the laminar flow frictional pressure drop with vertically and horizontally positioned coils. Akagawa et al.'s result fitted White's correlation while Watanabe et al.'s data fitted Ito's equation. Since White's and Schmidt's correlations agree with each other, we recommend these two correlations for calculation purposes in engineering.

2.1.2. Turbulent flow region

Compared with the laminar flow region, much work has been done in turbulent region for coils or curved tubes. To the author's knowledge, White (see [4]) presented the first correlation in this range with a smooth tube

$$f_c = 0.31\left[\log\left(\frac{Re}{7}\right)^{-2} + 0.04\left(\frac{d}{D}\right)^{0.5}\right]. \quad (5)$$

Ito [10] has suggested another equation from an experimental test of smooth tube

$$f_c = 1.216Re^{-0.25} + 0.116\left(\frac{d}{D}\right)^{0.5}. \quad (6)$$

Srinivasan et al.'s equation [11] is

$$f_c = 1.334Re^{-0.2}\left(\frac{d}{D}\right)^{0.1}. \quad (7)$$

The results of Eqs. (6) and (7) are very close and are higher than for White's correlation.

Ruffel (see [16]) suggested a correlation to calculate the turbulent flow frictional pressure drop in a coarse pipe

$$f_c = 0.06 + 0.12\left(\frac{d}{D}\right)^{0.275} Re^{-0.4}. \quad (8)$$

The research results of Akagawa et al. [4], Mori et al.[17], Watanabe et al. [8], Unal et al. [6] and Guo et al. [9] for curved pipes or helical coiled tubes show that Ito's correlation is of high accuracy. Therefore, we recommend Eq. (6) as the standard formula for the turbulent region.

2.1.3. Transition criterion between laminar and turbulent flow

The critical Reynolds number for the transition from laminar flow to turbulent flow in a curved pipe or helical coiled tube is important for the adoption of different formulas. Two criteria have been obtained. One is that suggested by Ito [10]

$$Re_{cr} = 20000\left(\frac{d}{D}\right)^{0.32}. \quad (9)$$

Srinivasan et al. [11] gives another

$$Re_{cr} = 2100\left[1 + 12\left(\frac{d}{D}\right)^{0.5}\right]. \quad (10)$$

The comparison of these equations shows an excellent agreement in the range of d/D lower than 0.05, while a little departure appeared in the range d/D higher than 0.05.

2.2. Two-phase flow region

Compared to single-phase flow, two-phase frictional pressure drop is more important for engineering practice and hence it has been comprehensively researched. The adopted working fluids include steam–water, air–water, SF_6–water and chemical compound (glycerine, butanol, etc.)–water. Table 1 lists the parameter ranges of these measurements.

Table 1
Previous researches on two-phase flow frictional pressure drop in helical coils

Authors	Working-fluid	d_{in} (mm)	D/d	Parameters	Results
Owhadi et al. [18]	Steam–water	12.5	20, 41.7	$G = 214$–850, $x = 0$–1.4	Meet with L–M equation for straight tube
Czop et al. [16]	SF_6–water	19.8	59	$P = 1$–1.35, $G = 500$–3000, $x = 0.04$–0.6	Meet with Chisholm equation for straight tube
Akagawa et al. [4]	Steam–water, chemical compound–water	12.5	53.2	Not mentioned	Meet with L–M equation for straight tube
Watanbe et al. [18]	Air–water	10	10.20	$G = 97$–646	Meet with L–M equation for straight tube
Unal [6]	Steam–water	18	46, 104, 186	$P = 14.7$–20.2, $G = 112$–1829, $x = 0.08$–1.0	Obtained a correlation
Nariai et al. [7]	Steam–water	14.3	41.6	$P = 2.0$–5.0, $W = 100$–500	Obtained a correlation
Chen and Zhou [5]	Steam–water	18	13.1, 24.8, 50.4	$P = 4.2$–22, $G = 400$–2000	Obtained a correlation
Guo et al. [9]	Steam–water	20	12, 24, 48	$P = 3.0$–14.0, $G = 250$–1400, $x = 0$–0.8	Obtained a correlation
Xin et al. [19]	Air–water	12.7, 19.1, 25.4, 38.1	34.48, 26.316, 17.54, 13.7, 9.434	$U_l = 0.008$–2.2, $U_g = 0.2$–50	Obtained a correlation

Owhadi et al. [18] have carried out a pioneering research of boiling two-phase flow frictional pressure drop in helical coils. The results were compared with the well-known Lockhart–Martienlli equation for the straight tube and a good agreement between them was obtained. Later, Nariai et al. [7] conducted an experiment in which the helical coiled tube was heated with liquid sodium. A coupled correlation including the sodium pressure was suggested. Unal et al. [6] have conducted the same measurement in a sodium-heated helical coiled tube and found that the diameter ratio d/D has little influence on the two-phase frictional pressure drop. This conclusion was confirmed by later researches of Chen and Zhou [5] and Guo et al. [9] employing an electrically heated helical coiled tube test section.

Unal et al.'s correlation [6] is expressed as

$$\Delta P_{tp} = 2(1 + b_1 b_2) f_l G^2/(d \cdot \rho_l), \tag{11}$$

where f_l is the frictional factor of single-phase flow and is calculated by the well-known Ito's correlation [10] and b_1 and b_2 are the non-dimensional parameters

$$b_1 = 3850 x^{0.01} Pr^{-1.515} Re_l^{-0.758}, \tag{12}$$

$$b_2 = 1 + Re_l^{0.1}(3.67 - 3.04 P_b), \tag{13}$$

$$P_b = P/P_{cr}, \tag{14}$$

where P_{cr} is the critical pressure ($P_{cr} = 22.115$ MPa for water).

Chen and Zhuo [5] have tested the steam–water two-phase flow frictional pressure drop in a vertical helical coiled tube with pressure from 3.0 to 14.0 MPa, and the following correlation is suggested

$$\Delta P_{tp} = \xi \cdot \Delta P_0 \tag{15}$$

where ΔP_0 is the frictional pressure drop when the single-phase liquid flow passes through the helical coils with the mass flow rate of a two-phase mixture. It is a non-dimensional parameter as follows:

$$\xi = 2.06\left(\frac{d}{D}\right)^{0.05} Re_{tp}^{-0.025}\left[1 + \alpha\left(\frac{\rho_g}{\rho_l} - 1\right)\right]^{0.8} \times \left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right]^{1.8}\left[1 + \alpha\left(\frac{\mu_g}{\mu_l} - 1\right)\right]^{0.2}. \tag{16}$$

Recently, Guo et al. [9] have conducted an experiment of horizontal helical coils in high-pressure loop with steam–water as the working fluid and another empirical equation was developed as

$$\Delta P_{tp} = \Phi_{lo}^2 P_{lo}, \tag{17}$$

where ΔP_{lo} is the frictional pressure drop when the liquid phase of a two-phase mixture flows through the helical coils only and Φ_{lo}^2 is the two-phase multiplier correlation

$$\Phi_{lo}^2 = 1 + (4.25 - 2.55 x^{1.5}) G^{0.34}. \tag{18}$$

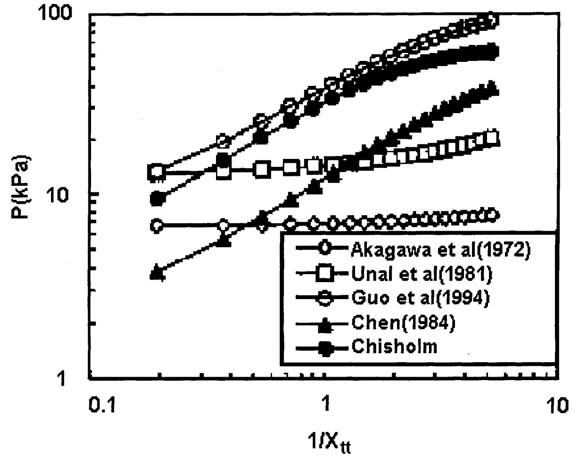

Fig. 1. The comparison of previously published correlations for frictional pressure drop of steam–water two-phase flow.

The comparison of Akagawa et al.'s, Unal et al.'s, Chen and Zhou's and Guo et al.'s correlations is shown in Fig. 1. It can be found that great differences exist among them and, in addition, these correlations are too sophisticated to be practically used except that of Guo et al. Therefore the improved correlation is required to estimate the frictional pressure drop in helical coils with a high accuracy and an easy operation. An experimental study of steam–water two-phase flow frictional pressure drop of helical coils was thus carried out in a high-middle pressure steam–water test loop. Two differently sized helical coils, of which the large one had with four helix axial directions, were studied. A new set of improved correlations is proposed to predicate the single-phase and boiling two-phase flow frictional pressure drop in helical coiled tubes.

3. Experimental apparatus and test conditions

3.1. Experimental facilities

The experiments have been conducted in a middle pressure steam–water two-phase flow loop operating in the National Laboratory of Multiphase Flow in Power Engineering, P.R. China, as shown in Fig. 2. The whole system was constructed by stainless steel tubes and was well isolated by asbestos. Water pumped from the main tank first passed through the surge tank and the flow rate measuring system. An S-shaped electrically heated preheater was employed to heat the working fluid to the required temperature. The steam–water two-phase flow mixture was cooled by a casing-pipe condenser and then returned to the main tank (see Fig. 2).

Two different-sized helical coiled tube test sections were made from stainless steel of 1Cr18Ni9Ti and were

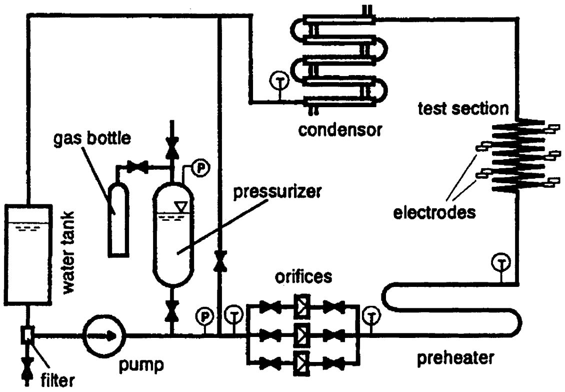

Fig. 2. Schematic diagram of test loop.

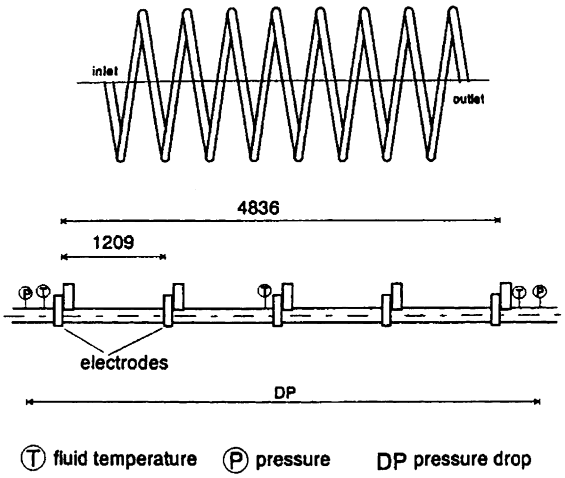

Fig. 3. Schematic diagram of helical coiled tube test section.

fabricated with great care (see Fig. 3). Fine-sized sand was pro-filled to well assure the smallest deformation of the tube cross-section during the bending process. The structural parameters of two tested helical coiled tubes are indicated in Table 2.

The experimental instrumentation can be outlined as follows. The system mass flow rate was measured by three standard orifices, enabling a large flow range and located at the inlet of the preheater. These orifices were well calibrated by the weighting method before experiment. Another throttle orifice was installed at the inlet of the test section to suppress the occurring possibility of two-phase instabilities. A group of differential pressure transducers (electrical-capacity type) were employed to measure the pressure drops of orifices and test sections. A pressure transducer (electrical-capacity type) was used to measure the inlet pressure of the test section. The differential pressure drop and pressure transducers were also well calibrated by a standard buoyancy ball differential pressure meter and standard oil hydraulic pressure gauge, respectively. In order to monitor the bulk temperature and to calculate the outlet fluid parameters and mass quality, three K-type armored thermocouples (0.5 mm NiCr–NiSi wires) were installed at the inlet, center and outlet positions of the test sections.

Table 2
Structural parameters of the test sections

Parameters	Large coil	Small coil
Total coil number	8	18
Heated coil number	6	18
Total length (mm)	4836	7560
Heated length (mm)	6448	7560
Coil diameter (mm)	256	132
Elevated angle (deg)	4.27	5.36
Tube inner diameter (mm)	11	10
Wall thickness (mm)	2	2
Helix axial angles (deg)	0.45, 90, −45	0

The present experiments were conducted under the following parameter ranges: system pressure $P = 0.5–3.5$ MPa, single-phase mass flow rate $G = 300–4300$ kg/m^2 s, two-phase mass flow rate $G = 150–1760$ kg/m^2 s, wall heat flux $q_w = 0–540$ kg/m^2, outlet Mass quality $x_{out} = -0.01–1.2$.

In order to test the influence of helix axial directions on the frictional pressure drop, the large coils were oriented in four inclinations, namely, horizontal (0°), 45° upward inclined, upward vertical and 45° downwards inclined.

3.2. Experimental uncertainty analysis

In the present test, the quantities measured directly were flow rate, pressure drop, pressure, and bulk temperature and electrical power.

The mass flow rate was measured by a set of orifices, which were calibrated with the weighting method. Its uncertainty was estimated to be less than 4.5%. Some differential pressure drop transducers were used to measure the pressure drops with an accuracy of ±2.5%. The measurement of electrical current was carried out by a set of electromagnetic-induction current transducer, which had an accuracy of 4.5%. The overall uncertainties of frictional factor f_c and frictional multiplier Φ^2_{lo} were estimated to 5.29% and 8.75%, respectively.

4. Results and discussion

4.1. Frictional pressure drop of single-phase flow

Many studies have been reported for single-phase frictional pressure drop of helical coils in the literature [10,11,16,20]. However none of them reach the range of

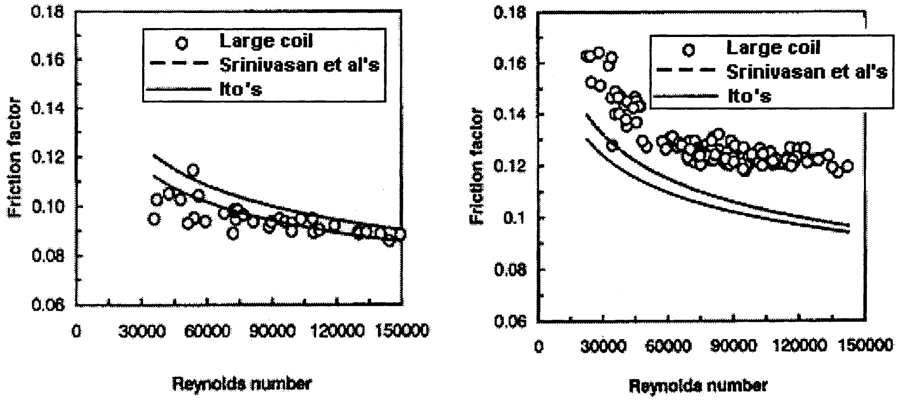

Fig. 4. Comparison of frictional factor for our experimental data with Ito's and Srinivasan et al.'s correlations.

Reynolds number greater than 1.5×10^5. In the present tests, the Reynolds number ranged from 1×10^5 to 4×10^5 to obtain the frictional pressure drop of high Reynold numbers regions. The critical Reynolds number Re_{cr} was estimated with Eqs. (9) and (10). Both relations indicate a value close to 7300 for a large coil and 8760 for a small coil; thus the whole data of our experiments fall into the turbulent region.

Fig. 4 shows the single-phase frictional pressure drop which resulted from the horizontally placed small and large coils. The frictional factor is calculated by following equation

$$\Delta P = \frac{f_c}{4} \cdot \frac{n\pi D}{d} \cdot \frac{\rho u^2}{2}. \tag{19}$$

For comparison purpose, Ito's [10] and Srinivasan et al.'s [11] correlations are also presented in this figure. It can be seen that Srinivasan's correlation meets well with the experiment data of large coil, while Ito's correlation is a little higher than our data. However, these two correlations depart from the data of small coils significantly. This difference is even pronounced in the high Reynolds number region. These results indicate that Ito's and Srinivasan et al.'s correlations cannot efficiently reflect the effect of coil diameter.

Single-phase frictional pressure drops of large diameter helical coiled tube with four different helix axial directions, including horizontal, 45° upward inclined, 45° downwards inclined and vertical upward, are presented in Fig. 5. This demonstrated that the 45° upward-inclined one gives a little high frictional pressure drop, and the vertical-upward one has the lowest value, while the other two coils have values between them. The frictional pressure drop of enlarged Reynolds number region was tested for 45° downward-inclined coils. It is found that Srinivasan et al.'s correlation accurately predicates the frictional factor of this region while Ito's correlation is a little lower than our data. However, the

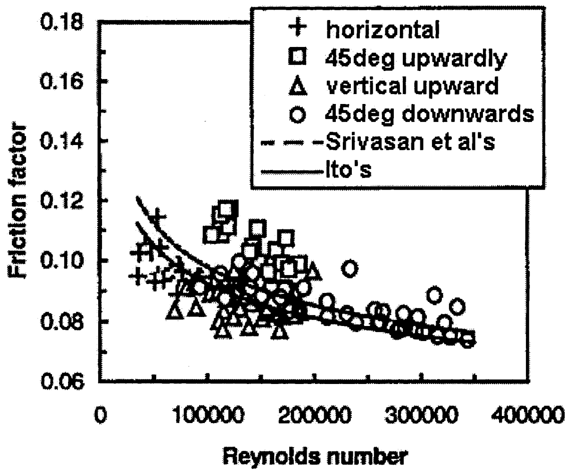

Fig. 5. Frictional factor for helical coiled tubes with different helix axial inclinations.

difference between these four helix axial inclinations is less than 12%. Therefore, inclination angles need not be comprised of the frictional pressure drop correlation.

Summarizing the whole data obtained from two helical coiled tubes and four different helix axial inclination angles, a better correlation is presented to fit our experiment data

$$f_c = 2.552 Re^{-0.15} \left(\frac{d}{D}\right)^{0.51}. \tag{20}$$

4.2. Fractional pressure drop of two-phase flow

Due to the effect of secondary flow, the two-phase flow frictional pressure drop in helical coils is greater than that of a straight tube. When the axis of helical coils is located in various directions, shapes of the secondary flow are different: thus, the two-phase flow frictional pressure drop in helical coils with various helix axial angles differed from one other as well.

Generally, a two-phase frictional multiplier is employed to correlate the frictional pressure drop of two-phase flow. Its definition is

$$\Phi_{lo}^2 = \frac{\Delta P_{tp}}{\Delta P_0}, \tag{21}$$

where ΔP_{tp} is the two-phase flow frictional pressure drop of helical coils, and ΔP_0 is the frictional pressure drop of single-phase fluid passing through the tube with the mass flow rate equal to that of the total two-phase mixture.

Fig. 6 shows the two-phase frictional multiplier of four differently inclined large diameter coils, where X_{tt} is the Martinelli parameter

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1}, \tag{22}$$

where x is the averaged mass quality of the two-phase region and is calculated from the following equation

$$x = \frac{x_{in} + x_{out}}{2}, \tag{23}$$

where x_{in} and x_{out} are the inlet and outlet mass qualities of the two-phase region, respectively $x_{in} = 0$. Calculations are started from the initial point of boiling.

A comparison of the experimental data shows that the horizontal helical coils have the smallest frictional pressure drop while the value of the 45° downwards-inclined coil is about 70% greater than that of horizontal helical coils. The vertical-upward and 45° upward-inclined coil have a value between the two.

Fig. 7 indicates the relationship between the averaged mass quality and the two-phase frictional multiplier of small and horizontally positioned large coils. It is seen that, in the range of $x < 30$, the two-phase frictional multiplier increases significantly with averaged mass quality, while in the range of $x > 0.3$, a slightly smoother relation appears. The increase in system pressure remarkably decreases the frictional pressure drop, especially in low system pressure conditions. Fig. 8 shows the relationship between the two-phase frictional multiplier and averaged mass quality of four differently positioned large coils.

During the past decades, some correlations have been published to calculate the two-phase flow frictional pressure drop in helical coils. However, the results obtained from these correlations are very different (as shown in Fig. 1) and these correlations are too sophisticated to be used practically. Therefore, an improved correlation is required to meet the engineering utilization.

Chen's [21] semi-theoretical equation is considered as a good one for calculating the two-phase flow frictional pressure drop in straight tubes, and has been indicated as the Chinese boiler hydrodynamic calculating method. Its expression is

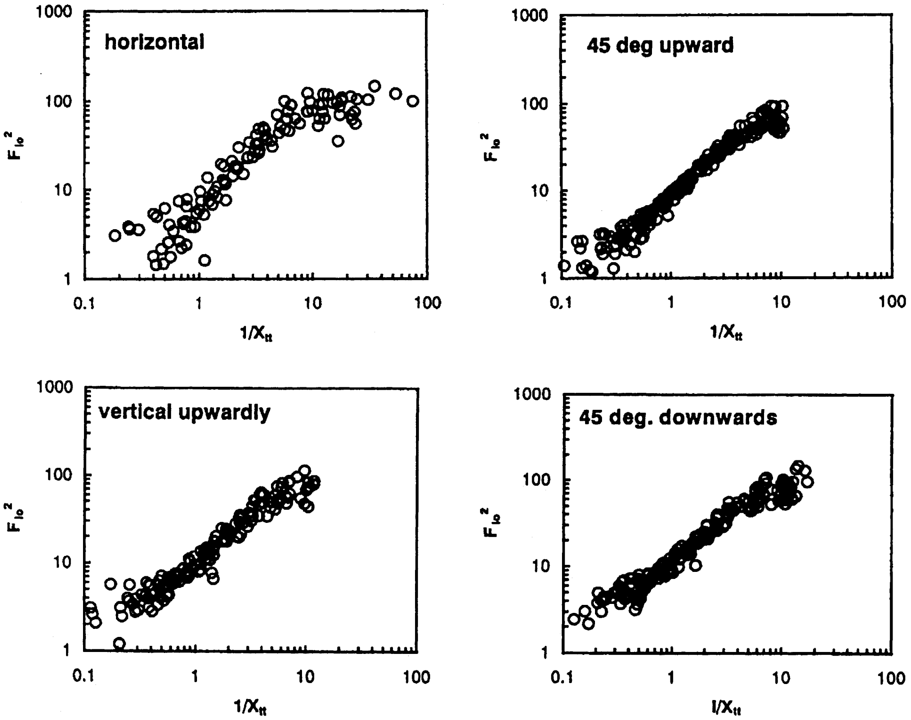

Fig. 6. Frictional pressure drop in helical coiled tubes with different helix axial directions.

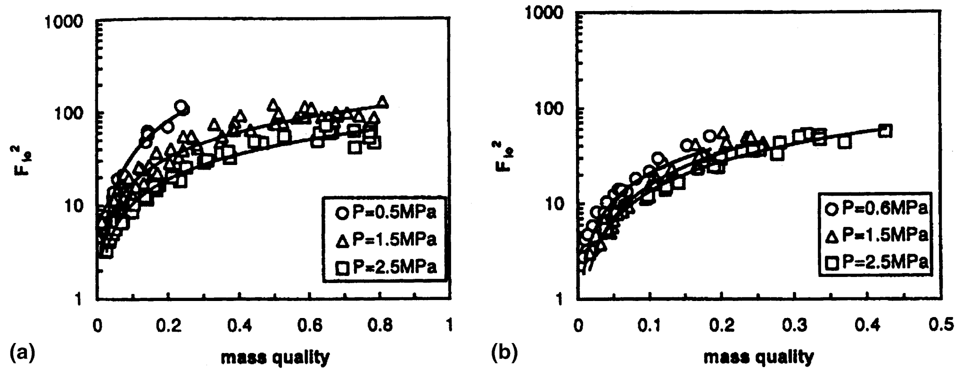

Fig. 7. Relation of averaged mass quality and two-phase flow multiplier of horizontal helical coiled tubes.

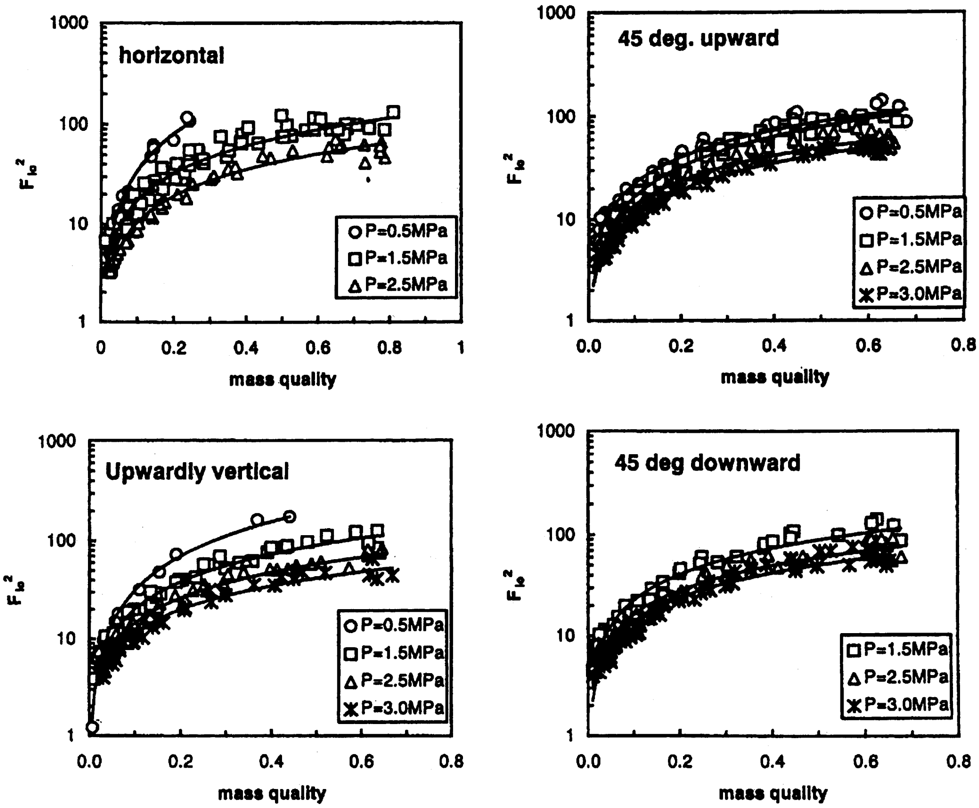

Fig. 8. Relations between averaged mass quality and two-phase flow frictional multiplier of helical coiled tubes with different helix axial inclinations.

$$\Phi_{\mathrm{lo}}^2 = \frac{\Delta P_{\mathrm{tp}}}{\Delta P_0} = \psi\left[1 + x\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}} - 1\right)\right], \tag{24}$$

where ψ is a semi-theoretical coefficient

$$\psi = 1 + \frac{x(1-x)((1000/G) - 1)(\rho_{\mathrm{l}}/\rho_{\mathrm{g}})}{1 + (1-x)((\rho_{\mathrm{l}}/\rho_{\mathrm{g}}) - 1)} \quad \text{for } G \leqslant 1000, \tag{25a}$$

$$\psi = 1 + \frac{x(1-x)((1000/G) - 1)(\rho_{\mathrm{l}}/\rho_{\mathrm{g}})}{1 + (1-x)((\rho_{\mathrm{l}}/\rho_{\mathrm{g}}) - 1)} \quad \text{for } G > 1000. \tag{25b}$$

Based on the comparison of this correlation with our experimental data, we found it to accurately estimate the influence of important parameters such as mass quality and system pressure, although its value is small in comparison with our experimental data. Therefore, Chen's correlation is modified to correlate the boiling two-phase flow frictional pressure drop in helical coiled tubes

$$\Phi_{\mathrm{lo}}^2 = \frac{\Delta P_{\mathrm{tp}}}{\Delta P_0} = \psi_1 \psi \left[1 + x \left(\frac{\rho_1}{\rho_{\mathrm{g}}} - 1 \right) \right], \tag{26}$$

where ψ is a coefficient calculated by Eqs. (25a) or (25b). ψ_1 is an empirical correct coefficient to exhibit the feature of helical coils and is deducted from our experimental data of two different-sized coils and their four positions. We have

$$\psi_1 = 142.2 \left(\frac{P}{P_{\mathrm{cr}}} \right)^{0.62} \left(\frac{d}{D} \right)^{1.04}. \tag{27}$$

It is difficult to include the inclination angles of helical coils which have not appeared in the above correlations. The comparison indicates the largest departure of ±40% between the predicted value and the experimental data of two different sized coils and their four inclination angles.

5. Conclusion

Single-phase water and steam–water two-phase flow frictional pressure drops are studied in two helical coiled tubes in which one is placed in four helix axial inclinations. Experimental data show that single-phase frictional pressure drop of small coils has a higher value than that of the large one, and this difference is even more pronounced in high Reynolds number region. A helical coiled tube positioned at 45° upward inclined exhibits a little higher frictional pressure drop: however, the difference among four inclined coils is less than 12%. The boiling two-phase flow frictional pressure drop is also higher in small diameter coils and it is affected by system pressure and mass quality. Comparison of experimental data shows that the horizontal helical coils have the smallest frictional pressure drop while the value of the 45° downwards inclined coil is about 70% greater than that of horizontal helical coils. The vertical-upward and 45° upward-inclined coil have a value between the two. Improved correlations have been proposed to estimate single-phase and two-phase frictional pressure drops in helical coiled tubes.

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