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An experimental study of flow pattern and pressure drop for flow boiling inside microfinned helically coiled tube

Wenzhi Cui [a], Longjian Li [a], Mingdao Xin [a], Tien-Chien Jen [b,*], Quan Liao [b], Qinghua Chen [b]

[a] College of Power Engineering, Chongqing University, Chongqing 400044, China
[b] Department of Mechanical Engineering, University of Wisconsin, Milwaukee, WI 53211, USA

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Abstract

In this paper, flow patterns and their transitions for refrigerant R134a boiling in a microfinned helically coiled tube are experimentally observed and analyzed. All the flow patterns occurred in the test can be divided into three dominant regimes, i.e., stratified-wavy flow, intermittent flow and annular flow. Experimental data are plotted in two kinds of flow maps, i.e., Taitel and Dukler flow map and mass flux versus vapor quality flow map. The transitions between various flow regimes and the differences from that in smooth straight tube have also been discussed. Martinelli parameter can be used to indicate the transition from intermittent flow to annular flow. The transition from stratified-wavy flow to annular or intermittent flow is identified in the vapor quality versus mass flux flow map. The flow regime is always in stratified-wavy flow for a mass flux less than 100 kg/m^2 s.

The two-phase frictional pressure drop characteristics in the test tube are also experimentally studied. The two-phase frictional multiplier data can be well correlated by Lockhart–Martinelli parameter. Considering the corresponding flow regimes, i.e., stratified and annular flow, two frictional pressure drop correlations are proposed, and show a good agreement with the respective experimental data.

Keywords: Flow boiling; Flow pattern; Pressure drop; Helically coiled tube; Microfin tube

1. Introduction

On the cases of intube convective boiling or condensation, accurate modeling and trustworthy evaluation of heat transfer and pressure drop characteristics require precise predictions of the local two-phase flow patterns, since distinct flow regimes can be characterized by quite different flow and heat transfer mechanisms. Therefore, studies of two-phase flow patterns and their transitions during intube flow boiling and condensation have gained increasing interest for several decades. Kattan et al. [1] proposed a diabatic flow pattern map for evaporation (boiling) in horizontal straight smooth tube. They stated that their flow pattern map was developed based on flow pattern data for five different refrigerants, including R134a. Muzzio et al. [2] investigated the flow patterns in flow boiling and convective condensation of refrigerant R22 in a microfin tube. The present authors' research group have developed a new kind of cross-grooved microfin tube, called three-dimensional (3-D) microfinned tube, and have done a lot of investigations on flow boiling and convective condensation flow patterns in such kind of straight tubes, such as Zhou and Xin [3] and Chen et al. [4].

Because of the high efficiency in heat transfer and compactness in volume, helically coiled tubes are used extensively in heat exchangers, nuclear reactors, solar collectors, and the food, drug and refrigeration industries. Comparing with the extensive studies in straight tubes, the investigation of two-phase flow patterns, especially diabatic two-phase flow patterns, in helically coiled tubes is insufficient. In a recently published review paper [5], more than one hundred papers have been reviewed in details. However, there is none of reviewed papers deals with flow

* Corresponding author. Tel.: +1 414 229 2307; fax: +1 414 229 6958.
E-mail address: jent@uwm.edu (T.-C. Jen).

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Nomenclature

d_i	inner diameter of tube, m
f	friction factor
F_{td}	modified Froude number, defined as Eq. (2)
g	gravity acceleration, m s^{-2}
G	total mass flux, kg/m^2 s
u	velocity, m s^{-1}
x	vapor quality
X_{tt}	Lockhart–Martinelli parameter

Greek symbols

ρ	density, kg m^{-3}
μ	kinetic viscosity, Pa s
γ	helix angle of the coiled tube, degree
ε	void fraction
Φ_{lo}	two-phase frictional multiplier
ΔP	pressure drop gradient, Pa/m

Subscripts

l	liquid
in	inlet
out	outlet
tp	two-phase condition
v	vapor

boiling or condensation flow patterns in helically coiled or even curved tube. In fact, for design purpose, it is important to know the flow pattern and pressure drop information in helically coiled tube.

In the open literature, most researches on two-phase flow in curved ducts are adiabatic gas and liquid flow, such as the studies of Whalley [6] and Xin et al. [7,8], they all used air and water as the experimental fluids. Some researchers, such as Jensen and Bergles [9], Guo et al. [10], and Zhao et al. [11], have studied the heat transfer and pressure drop characteristics of steam-water flow in helical tubing. In the authors' knowledge, however, investigations on diabatic two-phase flow of refrigerant in helically coiled tube have rarely been conducted. In this paper, therefore, the studies focus on the flow patterns and pressure drop for flow boiling of oil free refrigerant R134a, an environment-friendly refrigerant that has replaced R12 and in part R22, in a 3-D microfinned helically coiled tube.

2. Experimental setup

Fig. 1 shows the schematic diagram of the experimental apparatus used in this study. A complete description of the experimental test facility was also described in Li et al. [12] and Cui et al. [13].

The test data are obtained for evaporating conditions inside a 11.2 mm inner diameter microfinned helically coiled, copper tube test section that were heated by electrical resistance wire wound around the tube. The tested helically coiled tube is vertically positioned, i.e., refrigerant enters the test section from the lower inlet and exits from the upper outlet. The geometries of the test tube are listed in Table 1, where the two different values of fin height and

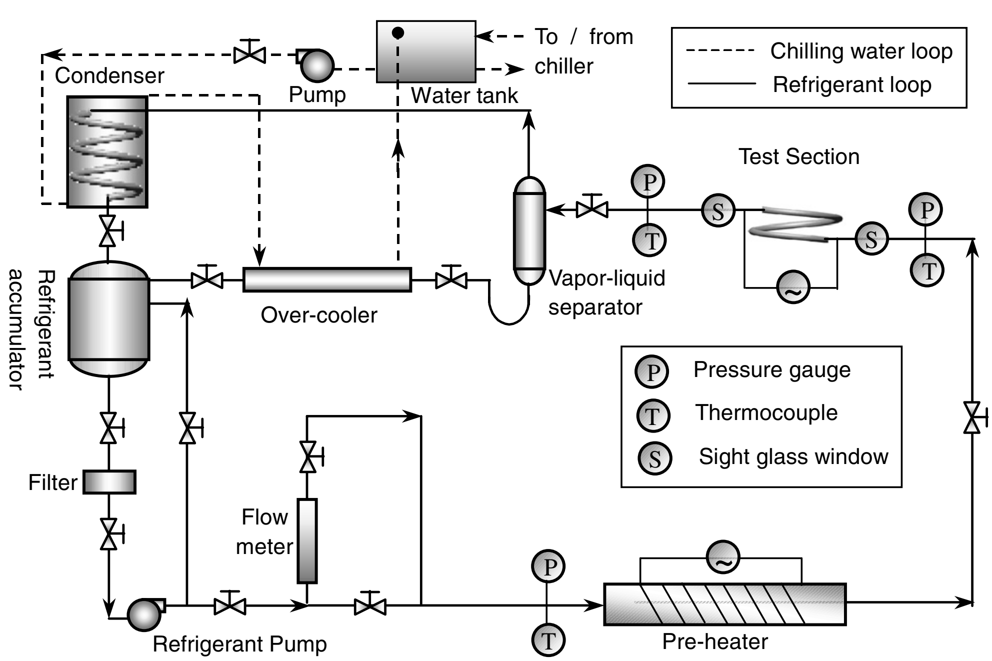


Fig. 1. Schematic diagram of the test loop.

fin helix angle refer to circumferential and axial fin parameters, respectively.

Two quartz glass windows are mounted at both ends of test section for flow pattern visualization. Fig. 2 shows the structure and the connection of the sight glass window. The inner diameter of the sight glass is equal to that of both test tube and the connections. A video camera and a digital camera are both used to record flow patterns in the sight glass. At the same time in test procedure, naked eye observations are also written down for references. The flow pattern data in this paper only refer to the records of the exit of the test section.

It is noteworthy to point out that flow patterns are observed through sight glasses which are not microfinned or curved, but nevertheless they are assumed as fully representatives of the flow regimes actually occurring at the test section exit. Indeed, we conjecture that the flow structure should experience only a minor disruption in passing to the glass tube, and the flow should not redevelop significantly through the sight glass because of its short length.

The two-phase pressure drop was measured with a differential pressure transducer, operating over the range from 0 to 20 kPa. It has an accuracy of ±0.5% FS (Full Scale) and they were calibrated in the laboratory before use. The flow rate of subcooled refrigerant before the preheater was measured with a float flow meter, which was accurate to ±2.5% of the reading. The saturation pressures at the inlet and outlet of the test section was measured with exact pressure gauges that were accurate to ±0.15% FS (1600 kPa) and the mean of these two pressures was used to determine the saturation temperature and hence the physical properties of the refrigerant.

The inlet vapor qualities of the refrigerant were obtained from energy balance on the electrical preheater. In this experiment, the inlet vapor qualities were always kept 0.05 or greater. The outlet were obtained from an energy balance on the electrically heated test section, which were found to be accurate to ±2.6% on average with a maximum deviation of ±5%. The tests were performed at selected values of mass velocity of 61, 90, 122, 183, 244 and 315 kg/m^2 s and the heat flux applied to the test tube was from 2.0 to 21.8 kW/m^2 as shown in Table 2.

Table 1
Test tube geometries

Parameters	Value
Outer diameter (mm)	12.7
Inner diameter (mm)	11.2
Number of fins	60
Circumferential fin pitch (mm)	0.59
Axial fin pitch (mm)	1.0
Fin height (mm)	0.25/0.3[a]
Fin helix angle (deg)	18/88.5[a]
Coil diameter (mm)	185
Coil pitch (mm)	50

[a] The two entries refer to circumferential and axial fin parameters, respectively.

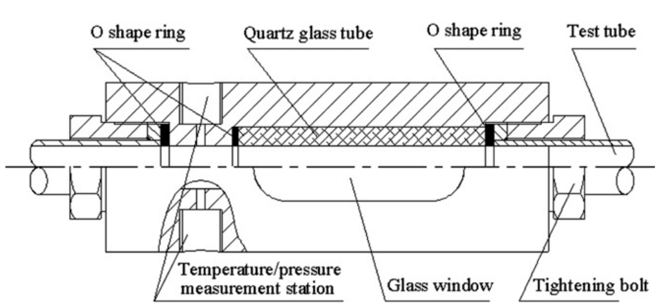


Fig. 2. Structure of sight glass window.

Table 2
The range of test conditions

Parameters	Range
Evaporating pressure (MPa)	0.50–0.58
Mass flux (kg/m^2 s)	61–315
Heat flux (kW/m^2)	2.0–21.8
Vapor quality (%)	0.05–92

3. Flow patterns

In the test, all the flow patterns observed in the microfinned helically coiled tube can be classified into bubbly, plug, stratified, stratified-wavy, intermittent and semi-annular and annular flow, respectively. Fig. 3 shows the photographs of four main flow patterns recorded by digital camera. Bubbly and plug flow only occur under very limited test conditions, such as large mass velocity with low heat flux. In view of the relatively short resident time for the above conditions, these two kinds of flow patterns are omitted or put into intermittent flow in the following discussion. In this paper, intermittent flow is also referred to as slug flow that is essentially a stratified-wavy flow pattern with large amplitude waves that wash the top of the tube. Stratified and stratified-wavy flows have a common mechanical essence; the only difference is the shear force on the two-phase interface is larger for the stratified-wavy flow pattern. Therefore, these two kinds of flow patterns are combined into stratified-wavy flow in the following discussion. And the annular flow pattern is that the liquid wets the entire tube periphery with the vapor flowing at the center of the tube. At some conditions in our experiment, although the annular flow has developed, the mass quality or void fraction is still low, at the lower part of tube there is a liquid pool rather than liquid film as occurred in full-developed annular flow. Such kind of flow is called semi-annular flow in our study.

Flow pattern maps are often used to depict the transitions of different flow patterns. Although different flow characteristics exist between two-phase flow in the straight tube and the helically coiled tube, the method for analyzing the flow pattern data for the straight tube is still used or

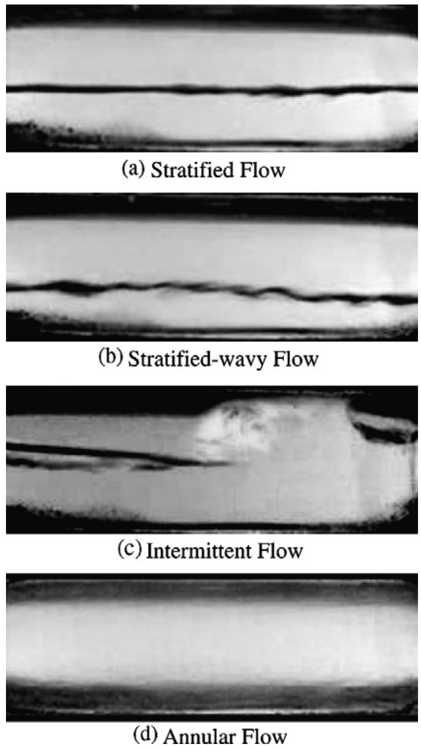


Fig. 3. Flow patterns in microfinned helically coiled tube.

modified to describe two-phase flow in helically coiled tubes.

Fig. 4 shows the flow pattern map following the model developed by Taitel and Dukler [14] for the present flow boiling in microfinned helically coiled tube.

In Fig. 4, the abscissa and ordinate are Martinelli parameter and modified Froud number, respectively. And their expressions are as following:

$$X_{\mathrm{tt}} = (\rho_{\mathrm{v}}/\rho_{\mathrm{l}})^{0.5}(\mu_{\mathrm{l}}/\mu_{\mathrm{v}})^{0.1}((1-x)/x)^{0.9} \tag{1}$$

where ρ_{v}, ρ_{l}, μ_{v} and μ_{l} are densities and viscosities of liquid and vapor phase, respectively. And x is the vapor quality. The above formulation is valid for both phases turbulent.

$$F_{\mathrm{td}} = u_{\mathrm{v}}\sqrt{\rho_{\mathrm{v}}/d_{\mathrm{i}}g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})} \tag{2}$$

where the vapor superficial velocity $u_{\mathrm{v}} = Gx/\rho_{\mathrm{v}}$, G is the mass flux of two-phase flow, d_{i} is the inner diameter of the test tube; and g is the gravity acceleration.

It can be found in this figure that transition between stratified-wavy flow and annular flow is not a simple relation of X_{tt} and F_{td}. Whereas, the Martinelli parameter X_{tt} can be used as the transition parameter to describe the later transition boundary, i.e., while X_{tt} is less than 0.7 the flow pattern becomes annular. The dash lines in Fig. 4 are the boundaries between stratified-wavy flow, intermittent flow and annular flow for smooth straight tube given by the original Taitel–Dukler flow pattern map. It can be seen that smooth straight tube and microfinned helically coiled tube have almost the same transition from stratified-wavy flow to annular flow, while the boundary between stratified flow and intermittent flow for straight tube is under that of helically coiled tube. For straight tube, the criterion of transition from intermittent flow to annular flow, proposed earlier by Taitel and Dukler [14], is $X_{\mathrm{tt}} = 1.6$. Kattan et al. [1] also concluded in the horizontal smooth tube that the intermittent to annular flow pattern transition was at a fixed value of the Martinelli parameter ($X_{\mathrm{tt}} = 0.34$ for both phases turbulent and $X_{\mathrm{tt}} = 0.51$ for laminar liquid and turbulent vapor flow, both are far from the one proposed by Taitel and Dukler [14]).

Alternatively, to better identify flow patterns during the evaporation process at different mass velocities and to make the map a more useful research and design tool, the axes of the Taitel and Dukler flow pattern map have been converted to mass flux versus vapor quality (similar to how local flow boiling coefficients are plotted, i.e., heat transfer coefficient versus vapor quality) as reported by Kattan et al. [1] and later improved by Zurcher et al. [15].

Fig. 5 shows such kind of flow map. This map indicates the influence of stratification at low flow rates (i.e., $G < 100\ \mathrm{kg/m^2\ s}$) in the present test tube. The visual observation of the flow through the sight glass indicated that for

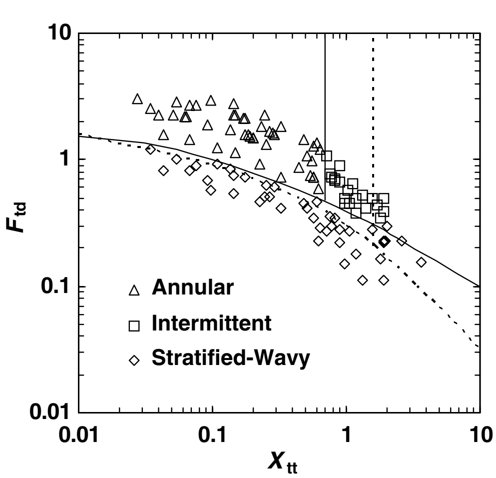


Fig. 4. Taitel–Dukler flow map for the experimental data.

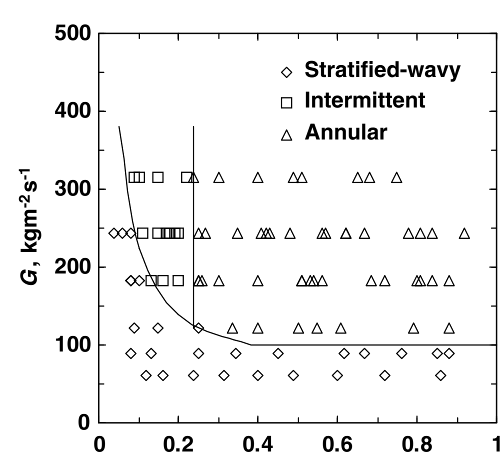


Fig. 5. G–x flow map for the experimental data.

mass velocities less than 100 kg/m^2 s, the flow was predominantly stratified, but as the mass velocity increased the flow became annular. The 100 kg/m^2 s mass velocity represents the transition value from stratified-wavy flow to annular for microfinned helically coiled tube. Kattan et al. [1] reported the similar results while the value of G is 150 kg/m^2 s for R134a flow boiling in horizontal smooth straight tube.

Another interesting result is the vapor quality ($x = 0.2$–0.3) can also depict the transition between intermittent flow and annular flow. This is consistent with the Taitel and Dukler flow map if only the Martinelli parameter is converted into vapor quality using the thermodynamic and transport properties of the refrigerant at the saturation temperature.

4. Pressure drop

Two-phase pressure drop gradients (pressure drop in a unit length) in the microfinned helically coiled tube are measured at various mass flux, inlet and outlet mass qualities and saturation pressures. Due to the relatively short test section, in fact, the experiments were conducted at different inlet qualities. Therefore, the comparison is based on pressure gradient instead of absolute pressure drop.

Compared with smooth straight tube, the two-phase flow pressure drop gradient in helically coiled tube is greater than that in straight tube for the corresponding experimental conditions in the entire tested range. This attributes to the effect of secondary flow in helically coiled tube, which makes the flow more chaotic in the tube. On the other hand, the microfinned surface of the test tube also increases the two-phase frictional pressure drop in the helically coiled tube.

The experimental results also suggest an increase of the pressure gradient with the increase of the exit quality and mass flux. Further comparison to straight tube shows that the increasing ratio with mass flux in coiled tube is also larger than that of a smooth straight tube.

The two-phase pressure drops for flows inside tubes are the sum of three contributions: gravitational (or static) pressure drop Δp_{grav}, momentum pressure drop Δp_{mom} and frictional pressure drop $\Delta p_{\mathrm{frict}}$ as

$$\Delta p_{\mathrm{total}} = \Delta p_{\mathrm{grav}} + \Delta p_{\mathrm{mom}} + \Delta p_{\mathrm{frict}} \tag{3}$$

For a vertically positioned coiled tube, the static pressure drop can be calculated as following:

$$\Delta p_{\mathrm{grav}} = g\rho_{\mathrm{l}} \tan\gamma(1-\varepsilon) \tag{4}$$

where γ is the helix angle of the coiled tube, which is 15.1° for the test tube. In the present study, the void fraction ε is obtained from a correlation suggested by Abdul-Razzak et al. [16], as

$$\varepsilon = \frac{1}{1 + 0.49X_{\mathrm{tt}}^{0.8036}} \tag{5}$$

The momentum pressure drop reflects the change in kinetic energy of the flow and is for the present case given by

$$\Delta p_{\mathrm{mom}} = G^2\left\{\left[\frac{(1-x)^2}{\rho_{\mathrm{l}}(1-\varepsilon)} + \frac{x^2}{\rho_{\mathrm{v}}\varepsilon}\right]_{\mathrm{out}} + \left[\frac{(1-x)^2}{\rho_{\mathrm{l}}(1-\varepsilon)} + \frac{x^2}{\rho_{\mathrm{v}}\varepsilon}\right]_{\mathrm{in}}\right\} \tag{6}$$

where G is the total mass flux of liquid plus vapor and x is the vapor quality.

Using the experimental values for the inlet and outlet vapor quality, the momentum pressure drop is calculable. Hence, the experimental two-phase frictional pressure drop is obtainable from Eq. (3) by subtracting the calculated and momentum pressure drop from the measured total pressure drop.

As can be seen from the above analysis, in most cases, it is of importance to obtain the calculating equation of frictional pressure drop, which is also the most important contribution to the total two-phase pressure drop. As stated by Guo et al. [10], although several correlations have so far been published to calculate the pressure drop in helically coiled tube, the results obtained from these correlations are rather different and these correlations are too sophisticated to be used in practice. On the other hand, none is developed based on the two-phase flow frictional pressure drop in microfinned helically coiled tube.

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

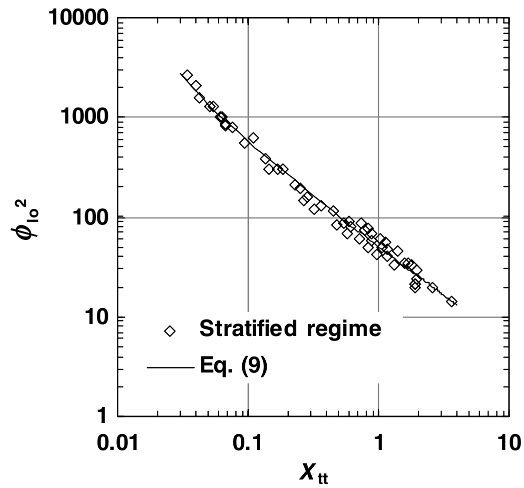
$$\Phi_{\mathrm{lo}}^2 = \frac{\Delta P_{\mathrm{tp}}}{\Delta P_{\mathrm{o}}} \tag{7}$$

where ΔP_{tp}, which can be measured in test, is the two-phase flow frictional pressure drop of helical coils, and ΔP_{o} is the frictional pressure drop of single-phase fluid passing through the tube supposing that only the liquid of the two-phase mixture flows in the same tube, as

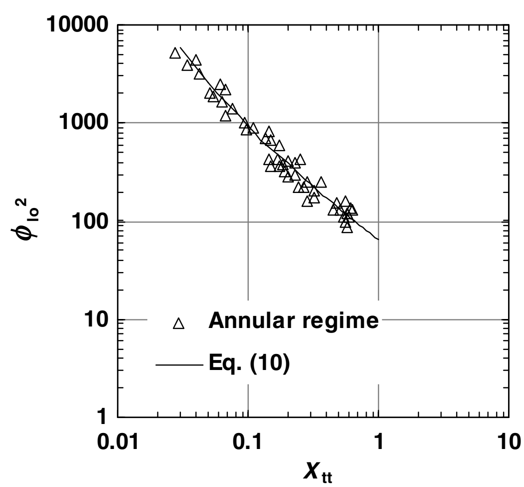
$$\Delta P_{\mathrm{o}} = -f_{\mathrm{l}}\frac{G^2(1-x)^2}{d_{\mathrm{i}}\rho_{\mathrm{l}}} \tag{8}$$

where f_{l} is the friction factor, which is calculated using the well known correlation proposed by Ito [17] for helically coiled tube.

As mentioned above, the flow patterns of flow boiling inside a tube evolve with the vapor quality, affecting the flow structures and the pressure drop. Therefore, correlating the experimental data according to different flow regimes can results in better agreement correlation of two-phase frictional multiplier. The experimental data were then divided into two parts according to the observed prevailing flow patterns, i.e., stratified and annular flow regime. Two frictional pressure drop correlations considering the corresponding flow regime were proposed as Eqs. (9) and (10), which referred to stratified and annular flow, respectively:



(a) Stratified flow regime



(b) Annular flow regime

Fig. 6. Pressure drop multiplier versus Lockhard–Martinelli parameter for microfinned helically coiled tube in stratified flow regime.

$$(\phi_{lo}^2)_{Stratified} = 1 + \frac{48.2}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{9}$$

$$(\phi_{lo}^2)_{Annular} = 1 + \frac{59.8}{X_{tt}} + \frac{3.5}{X_{tt}^2} \tag{10}$$

The predictions from the above correlations are shown in Fig. 6a and b with the experimental data of annular and stratified flow regimes. The correlations have mean absolute deviation of 12.5% and 18.2%, respectively.

The comparison between the experimental values of Φ_{lo}^2 and the predicted results is shown in Fig. 7. Most of the experimental data are within a deviation of ±20%, so Eqs. (9) and (10) can be used to calculate the frictional pressure drop with good accuracy in the present test range.

5. Conclusions

Two-phase flow regimes and pressure drop characteristics of refrigerant R134a boiling in a microfinned helically

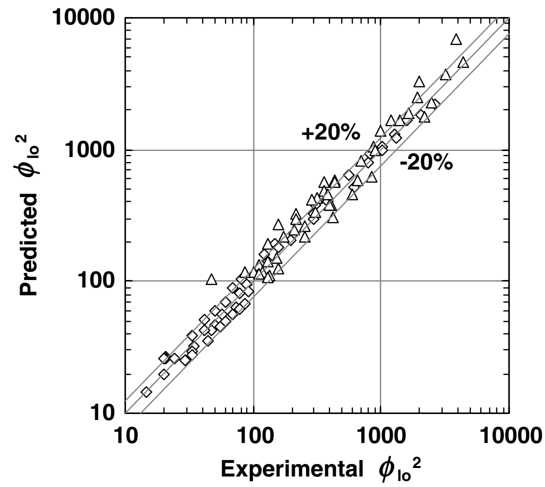


Fig. 7. Comparison of Eqs. (9) and (10) with present experimental results.

coiled tube are experimentally studied in this paper. The flow patterns are identified using visualization methods and grouped into three dominant regimes, i.e., stratified-wavy flow, intermittent flow and annular flow. Flow map is used to figure out the transitions of different flow patterns. Two kinds of usually used flow maps, i.e., Taitel and Dukler flow map and mass flux versus vapor quality (G–x) flow map, are chosen in this study. Martinelli parameter can be used to indicate the transition from intermittent flow to annular flow, which is $X_{tt} = 0.7$, whereas it is $X_{tt} = 1.6$ for straight tube. G–x flow map is recommended in this specific study, which is simpler and more useful. The transition from stratified-wavy flow to annular or intermittent flow is identified in G–x flow map. The flow regime is always in stratified-wavy flow for a mass flux less than 100 kg/m^2 s.

The frictional pressure drop data can be well correlated by Lockhart–Martinelli parameter. Based on the corresponding flow regimes, two two-phase frictional multiplier correlations with good accuracy are developed from the experimental data for stratified and annular flow regimes, respectively.

Acknowledgments

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