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https://hdl.handle.net/2324/1110

出版情報：九州大学工学紀要. 62 (1), pp.41-54, 2002-03-26. 九州大学大学院工学研究院
バージョン：

Memoirs of the Faculty of Engineering, Kyushu University, Vol. 62, No. 1, March 2002

Flow Pattern and Pressure Drop in Flow Boiling of Pure Refrigerants and Their Mixture in Horizontal Tube

by

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(Received December 25, 2001)

Abstract

An experimental investigation on the flow pattern and pressure drop was carried out for both an adiabatic and a diabatic two-phase flow in a horizontal tube with pure refrigerants R134a and R123 and their mixtures as test fluids. The measured frictional pressure drop in the adiabatic experiments increased in the *S*-curve as equilibrium vapor quality was increased. These data were compared with various correlations proposed in the past for the frictional pressure drop. Chisholm[1)] correlation considerally underpredicted the present data both for pure fluids and their mixtures in the entire mass flux range 150 to 600 kg/m^2s covered in the measurements, while Friedel[2)] correlation was found rather well to correlate the frictional pressure drop data among compared correlations. However a detailed examination showed Friedel correlation underpredicted the present data in the stratified and stratified-wavy flow regions at low vapor quality and overpredicted in the annular flow region at high quality. A new two-phase multiplier was developed from a dimensional analysis of the frictional pressure drop data measured in the adiabatic experiment. This new multiplier was found successfully to correlate the frictional pressure drop measured in the diabatic flow boiling experiments of pure refrigerants and their mixtures with a mean deviation of 20%.

Keywords: Flow Pattern, Mixture, Pressure Drop, Two-Phase Frictional Multiplier

1. Introduction

In the past decade, experimental studies were carried out for two-phase pressure drop in tubes to develop empirical or semi-empirical predictive methods that are applicable to the design of efficient heat exchanger in refrigeration and air-conditioning systems. As a result

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of these efforts, a large number of correlations for two-phase pressure drop in horizontal tube are available, but most of such correlations were developed on the basis of water-steam or water-air two-phase flow. Thus, general applicability of those correlations to arbitrary fluid remains in doubt because boiling two-phase flow phenomena are dependent on fluid properties.

The measured total pressure drop in boiling two-phase flow consists of two components, frictional pressure drop and accelerational pressure drop. The frictional pressure drop usually makes a main contribution to the total pressure drop while its precise prediction is not easy. On the other hand, the accelerational pressure drop result from the variation of momentum flux accompanied by phase change and its contribution is generally low as compared with the frictional pressure drop.

Two models are used in many cases to predict the frictional pressure drop in flow boiling is predicted; the homogeneous model that assumes equal phase velocity and the separate flow model that allows a slip velocity between two phases. Bo Pierre[3] employed the homogeneous model to developed a correlation from the measured pressure drop data with refrigerants R12, R22 and R502. Lockhart and Martinelli[4] originated the separate model and proposed their famous correlating method, which was later modified by Martinelli and Nelson[5] to predict the pressure drop in horizontal flow boiling. Jung et al[6] performed an experimental study on pressure drop in horizontal flow boiling of pure and mixed refrigerants of R22, R114, R12 and R152a, and developed a new correlation by modifying Martinelli and Nelson's correlation. The correlation showed a mean deviation of 8.4% in predicting their data.

The objectives of the present study are to obtain experimental data for flow pattern and pressure drop during flow boiling in horizontal tube with pure refrigerants R134a and R123 and their mixture as test fluids. The measured pressure data will be compared with various existing correlations. Finally, a new correlation will be developed to predict the measured data both for pure refrigerants and their binary mixtures in the present experiments.

2. Experimental Apparatus and Procedure

The experimental apparatus used in the present study is schematically shown in **Figure 1**. The circulation loop of test fluid consists of a reservoir tank, pump, flow meters, mixing chambers, preheaters, sight glass sections, the test section, condenser and other accessories.

Subcooled fluid in the reservoir tank is pumped through a strainer and the 1st preheater to the inlet mixing chamber where fluid temperature and pressure are measured. Then the fluid is heated in the 2nd preheater up to a prescribed enthalpy or vapor quality and then enters the heated test section where the fluid evaporates on the tube wall heated at uniform heat flux. Flow patterns of boiling two-phase fluid are observed at the upstream and downstream of the test section through glass tube of the same diameter as the test tube.

Figure 2 shows the test section, a 3 m-long stainless steel tube of 10 mm I.D. and 1.5 mm wall thickness, the central 2 m of which is the heat transfer section and is heated by directly passing stabilized AC that is supplied from a low-voltage and high-current transformer.

Tube wall temperature is measured at ten axial locations of the heat transfer section by Cromel-Alumel thermocouples spot-welded on the outer surface of the tube. The first location is 10 mm downstream of the heated section inlet, and succeeding nine locations are aligned at an equal interval of 200 mm. At each location, the tube temperature is measured at six peripherally different positions at angles of 0°(top), 45°, 90°(side), 135°, 180° (bottom) and 270°(another side) in the clockwise direction.

The inside temperature of the heated tube and heat flux to fluid are calculated from the

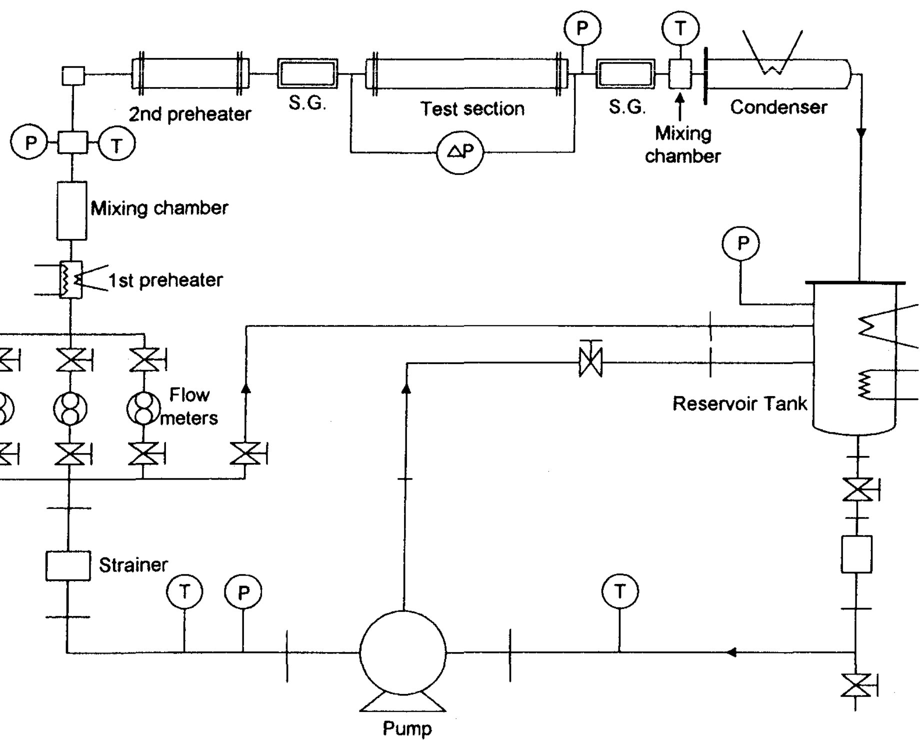


Fig. 1 Experimental apparatus

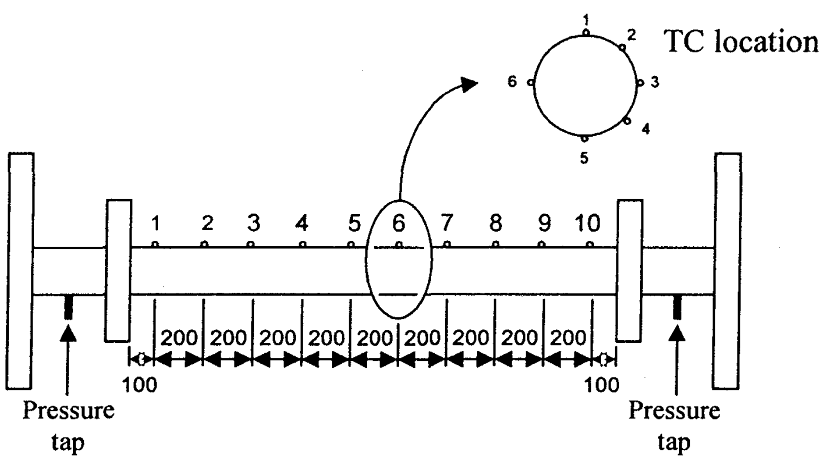


Fig. 2 Test section

outside wall temperature assuming one-dimensional heat conduction and accounting for uniform heat generation in the wall and heat loss to the surroundings.

Although the test section and preheater are well insulated with glass fiber, heat loss in the heated test section is inevitable. It was calibrated as a function of the temperature difference between the tube wall and ambient room air, and used in the evaluation of tube inside temperature and heat flux.

The fluid temperature and pressure are measured in the mixing chambers at the inlet and exit of the test section. The pressure drops between the inlet and exit mixing chambers and across the pressure taps closely installed to the heated section are measured using differential pressure transducers. These data of fluid temperature and pressure are used to determine the local fluid temperature and pressure along the test section, as will be mentioned in the later.

Refrigerants R134a and R123 are selected as test fluids of pure components. They are respectively mixed as the more- and less-volatile components to constitute binary mixtures. Mole fractions of the more volatile component (R134a) in the mixture are set at 27, 49and

75%. Major parameters that affect heat transfer and pressure drop in flow boiling are mass flux G, heat flux q and vapor quality β. In the present experiment, the mass flux is set at 150, 225, 300 and 600 kg/m^{2}s, and heat flux is varied at 5, 10, 20 and 50 kW/m^2. Vapor quality covers zero to almost unity.

Flow pattern

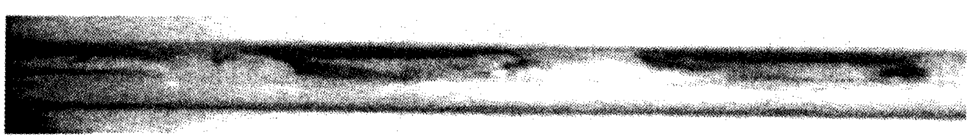
Flow patterns in the present experiments are observed through the sight glass tube downstream of the heated section. **Figure 3** shows typical pictures of flow patterns observed in the experiment. Observed patterns are classified into intermittent flow (I), stratified-wavy flow (SW), annular flow (A), and coexistence of stratified-wavy flow and annular flow (SW/A). Here, the intermittent flow patterns correspond to an alternative occurrence of slug and plug flows.

Flow pattern data are plotted on the mass flux versus quality map of **Figure 4**. The boundaries of respective flow patterns in the figure are by given Kattan et al.[7]. They modified the VDI[8] flow pattern map to develop a new map applied for evaporation in horizontal tubes, based on flow pattern data for five different refrigerants covering a wide range of mass flux and vapor quality. As seen in **Figure 4** the present data for mixtures are well predicted by flow map of Kattan et al.

3. Results and Discussions

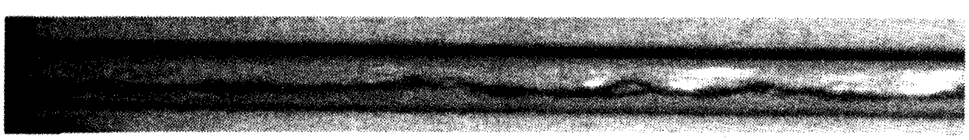
3.1 Frictional Pressure Drop

Total pressure drop in a horizontal tube during flow boiling consists of two components as given by

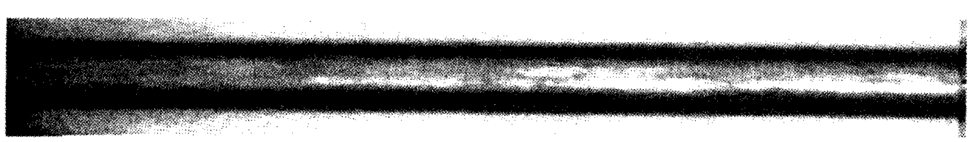


(a) Intermittent flow (G=600kg/m^{2}s, β_0=0.034)

(b) Stratified flow (G=300kg/m^{2}s, β_0=0.083)



(a) Stratified-wavy flow (G=300kg/m^{2}s, β_0=0.147)



(a) Annular flow (G=150kg/m^{2}s, β_0=0.908)

Fig. 3 Typical pictures of flow patterns

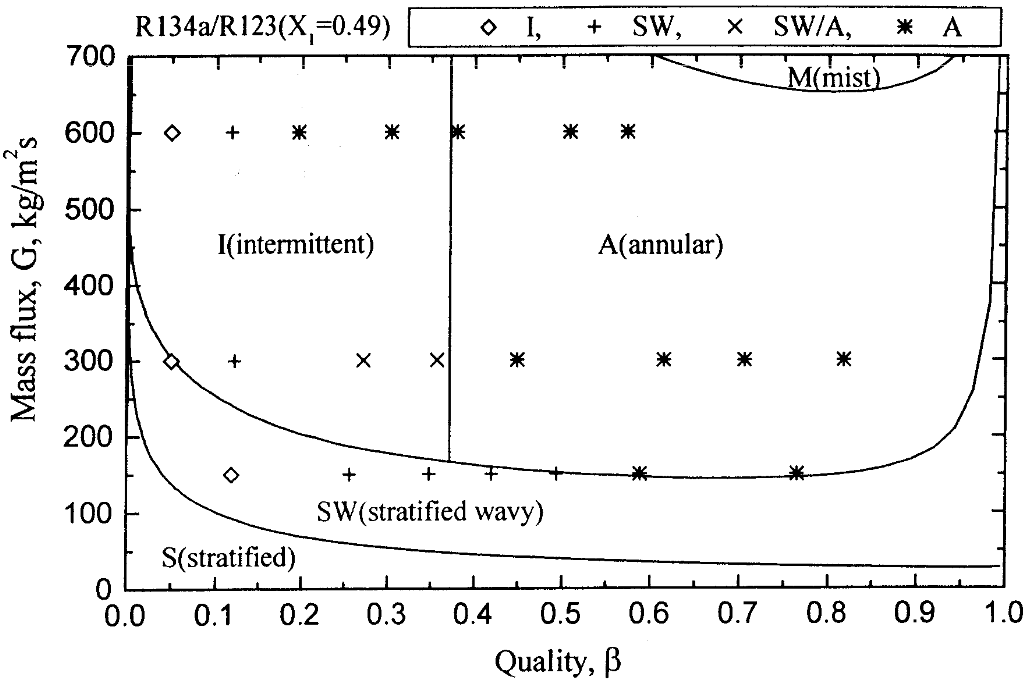


Fig. 4 Flow patterns on the G-βmap

$$\Delta P = \Delta P_f + \Delta P_a \tag{1}$$

where ΔP_f is the frictional pressure drop and ΔP_a is the accelerational pressure drop. The frictional pressure drop was measured in the adiabatic experiment where inlet vapor quality to the test section was varied by adjusting the power supplied to the preheater and vapor quality is kept constant in the non-heated test section between two pressure taps.

3.2 Adiabatic Pressure Drop

Figure 5(a), (b) and (c) indicate as a function of quality the frictional pressure gradient over the pressure taps measured under the adiabatic condition. It is seen from the figure that the pressure drop increases with an increase in vapor quality and mass flux. Vapor quality and mass flux dependency of frictional pressure gradient is similar among two pure refrigerants and their binary mixture although R134a indicates high pressure drop and R123 indicates low pressure drop in the entire quality region.

Two-phase pressure drop or pressure gradient are often expressed in terms of a two-phase multiplier. Thus the multiplier is defined as

$$\phi^2{}_{fo} = \frac{\Delta P_{TP}}{\Delta P_{fo}} \tag{2}$$

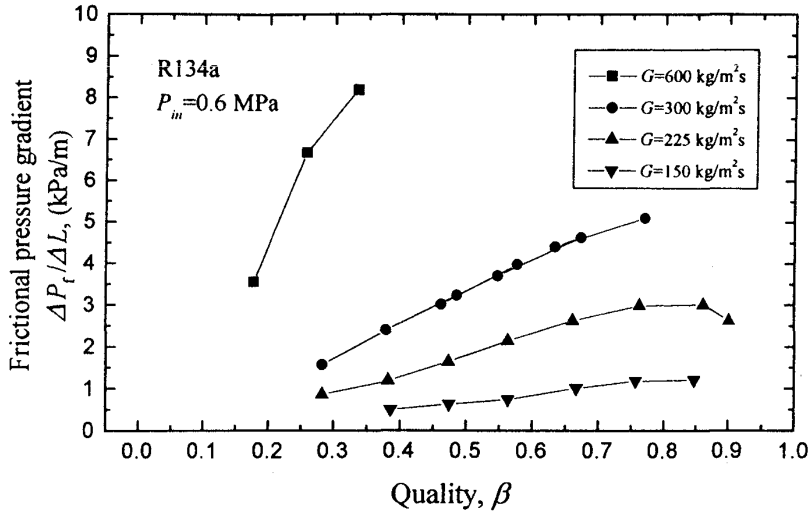
where ΔP_{TP} is the two-phase frictional pressure drop andΔP_{fo} is the single phase frictional pressure drop assuming two-phase fluid flows as liquid. Thus

$$\Delta P_{fo} = \frac{2 f_{fo} G^2 L}{D \rho_l} \tag{3}$$

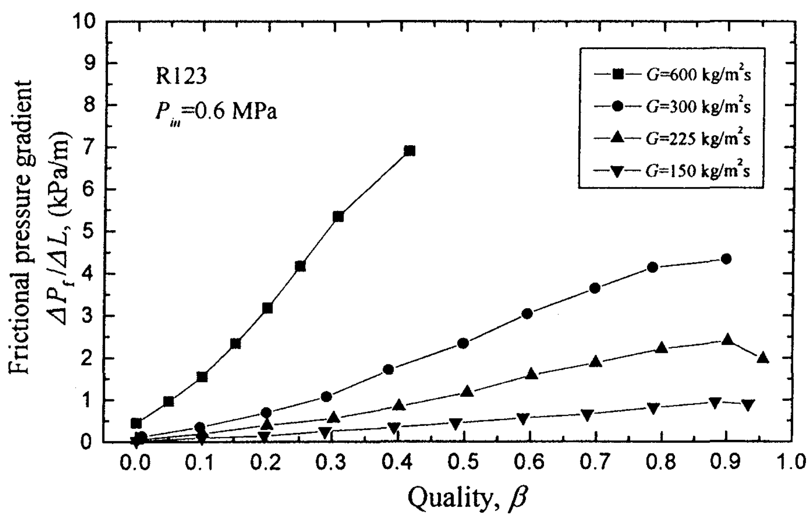
Here the friction factor for turbulent flow is given as

$$f_{fo} = 0.079 Re^{-1/4} \tag{4}$$

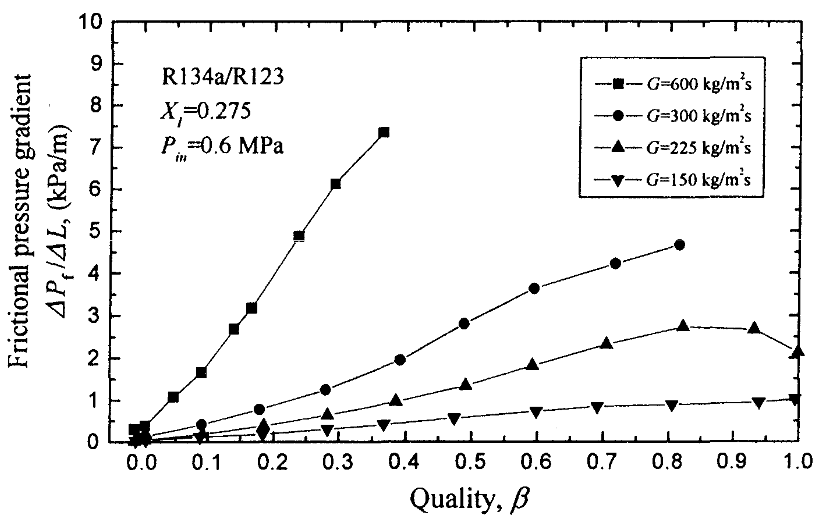
Figure 6(a), (b) and (c) show the two-phase frictional multipliers calculated according to equation (2) from the measured two-phase frictional pressure drops. **Figure 7**(a), (b) and



(a) R134a



(b) R123



(c) R134a/R123

Fig. 5 Variations of pressure gradient against quality

(c) compare the measured two-phase multiplier with several typical correlations. As seen in the figure the compared correlations vary quite widely. Both correlations of Lockhart-Martinelli and Martinelli-Nelson based on the separate flow model show highest multiplier with a non-leaner variation against vapor quality. On the other hand, the homogeneous flow model shows lowest multiplier among the compared correlations. Friedel correlation lies at the middle of other correlations with a nearly linear variation.

Under an assumption that the frictional pressure drop multiplier is a function of Martinelli parameter X_{tt}, the two-phase Froude number Fr_{TP} and two-phase Weber number We_{TP} the present data are analyzed to develop a new expression of multiplier. Thus

$$\phi^2{}_{fo}=f\,(Fr_{TP}, We_{TP}, X_{tt}) \tag{5}$$

Here three dimensionless parameters are given as

$$Fr_{TP}=\frac{G^2}{gD\rho^2{}_{TP}} \tag{6}$$

$$We_{TP}=\frac{G^2 D}{\sigma\rho_{TP}} \tag{7}$$

$$X_{tt}=\left(\frac{1-\beta}{\beta}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{8}$$

where ρ_{TP} is the homogeneous density defined as

$$\rho_{TP}=\left[\frac{\beta}{\rho_v}+\frac{1-\beta}{\rho_l}\right]^{-1} \tag{9}$$

The final form of the two-phase frictional multiplier correlated in this study becomes

$$\phi^2{}_{fo}=\frac{0.36\times\{0.6+(Fr_{TP}\times A)\}^{1.30}}{Fr_{TP}^{0.51}\cdot We_{TP}^{-0.031}}X_{tt}^{0.15} \tag{10}$$

where $A=-1.06\log(G)+7.04$ for $G\leqq 300$ kg/m^{2}s
$A=1260\times G^{-1.24}$ for $G>300$ kg/m^{2}s

Figure 8(a), (b) and (c) indicate the comparison between the measured frictional pressure drop and that calculated using equation (10). It is found from the Figure that the two-phase multiplier proposed in the present study predict satisfactorily the present data for the entire region of quality.

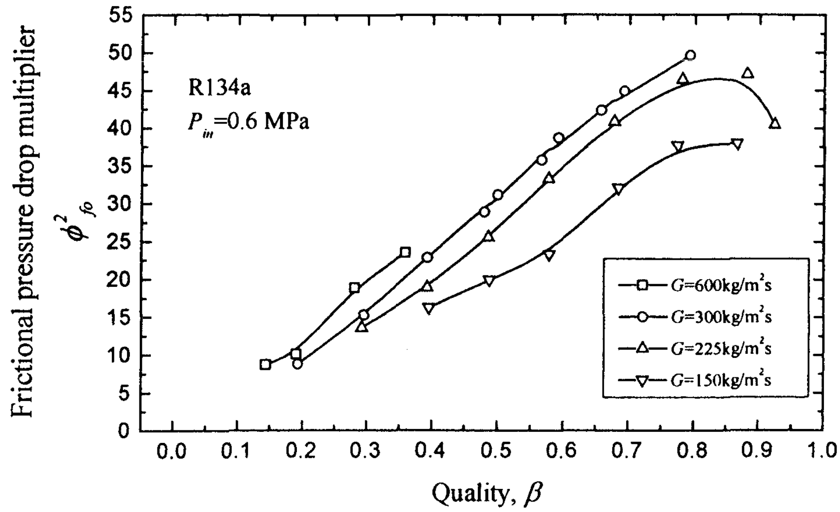
3.3 Diabatic Pressure Drop

The two-phase frictional pressure drop multiplier with a change of quality from β_i to β_o over a heated length L can be calculated from Eq (2) as

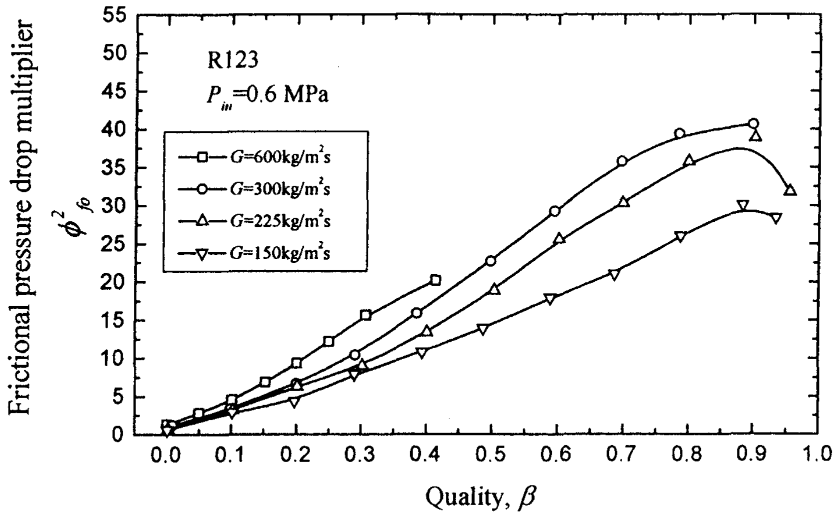
$$\bar{\phi}^2_{fo}=\frac{\Delta P_{TP}}{\Delta P_{fo}}=\frac{1}{\beta_o-\beta_i}\int_{\beta_i}^{\beta_o}\phi^2_{fo}d\beta \tag{11}$$

Figure 9 shows typical results of the measured total pressure drops for various values of heat flux. An inlet quality is nearly constant of 0.1 and mass flux is $G=300$ kg/m^{2}s. The acceralational pressure drop in the figure under the heated condition is evaluated from the following equation.

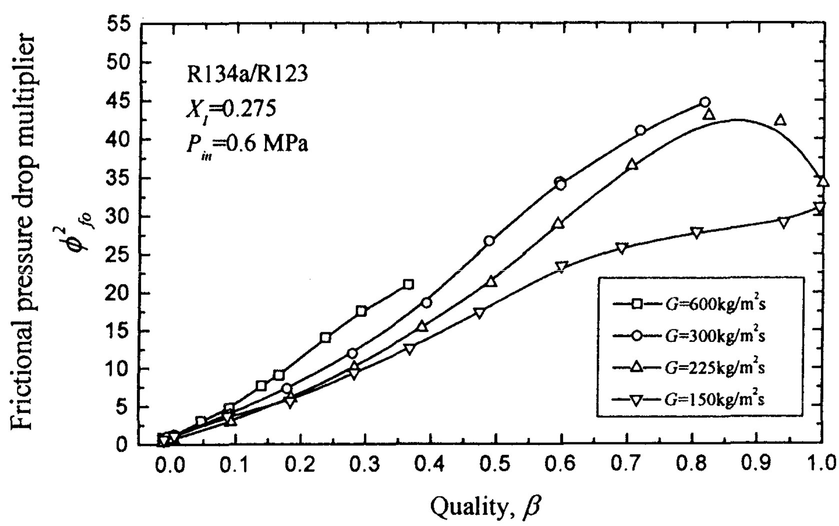
$$\Delta P_a=G^2\left[\left\{\frac{\beta^2}{\alpha\rho_v}+\frac{(1-\beta)^2}{(1-\alpha)\rho_l}\right\}_{out}-\left\{\frac{\beta^2}{\alpha\rho_v}+\frac{(1-\beta)^2}{(1-\alpha)\rho_l}\right\}_{in}\right] \tag{12}$$



(a) R134a

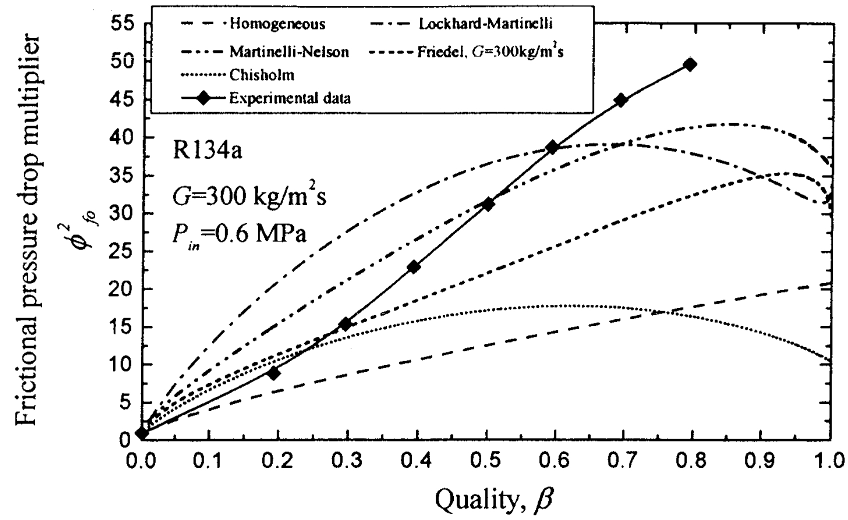


(b) R123

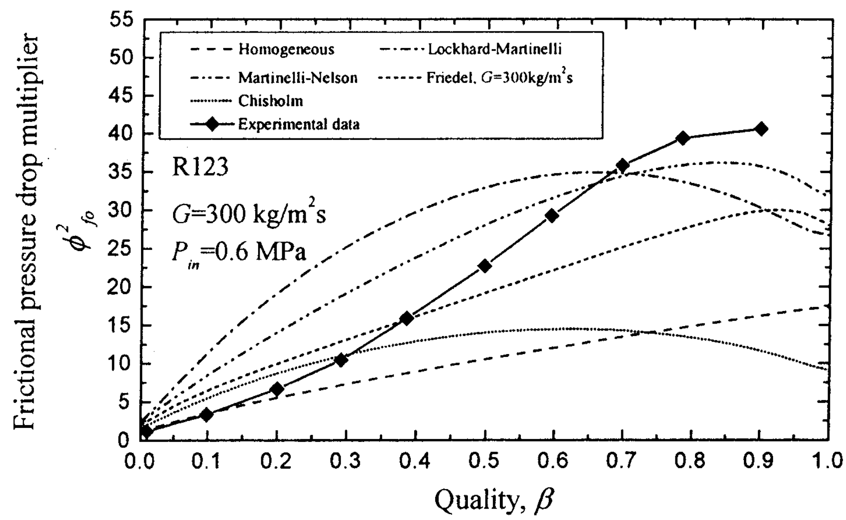


(c) R134a/R123

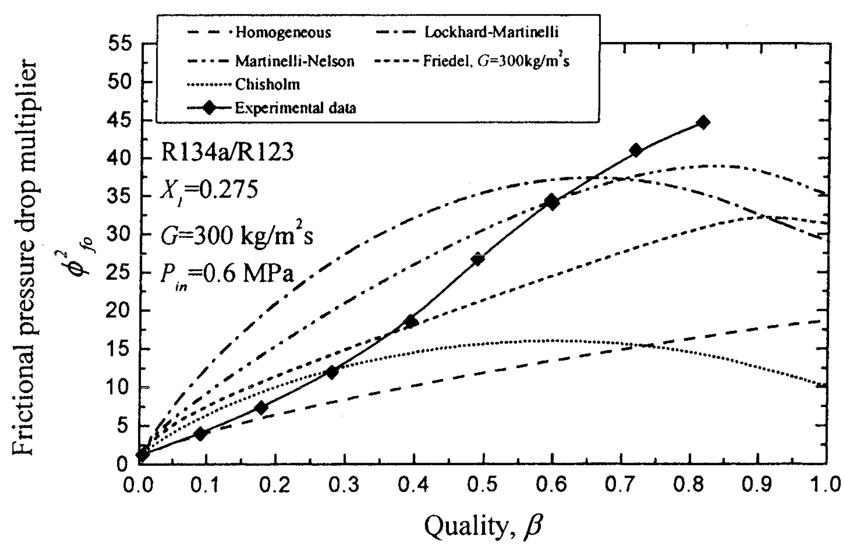
Fig. 6 Variations of the two-phase frictional multipliers against quality



(a) R134a

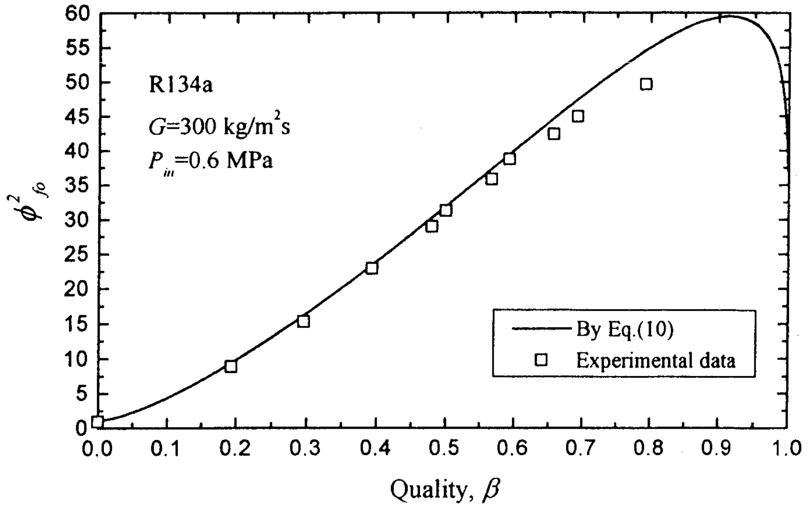


(b) R123

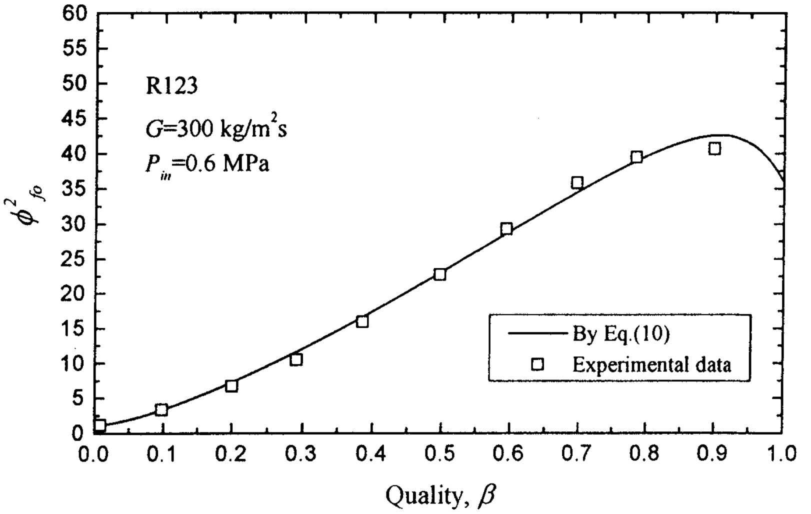


(c) R134a/R123

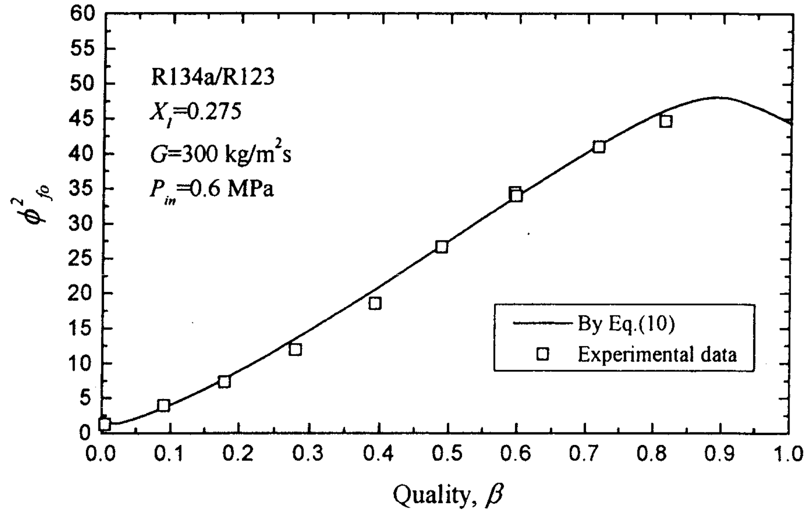
Fig. 7 Comparison between the measured frictional pressure drop multiplier and the prediction from several correlations



(a) R134a



(b) R123



(c) R134a/R123

Fig. 8 Comparison between the measured frictional pressure drop multiplier and the prediction from a new correlation (10)

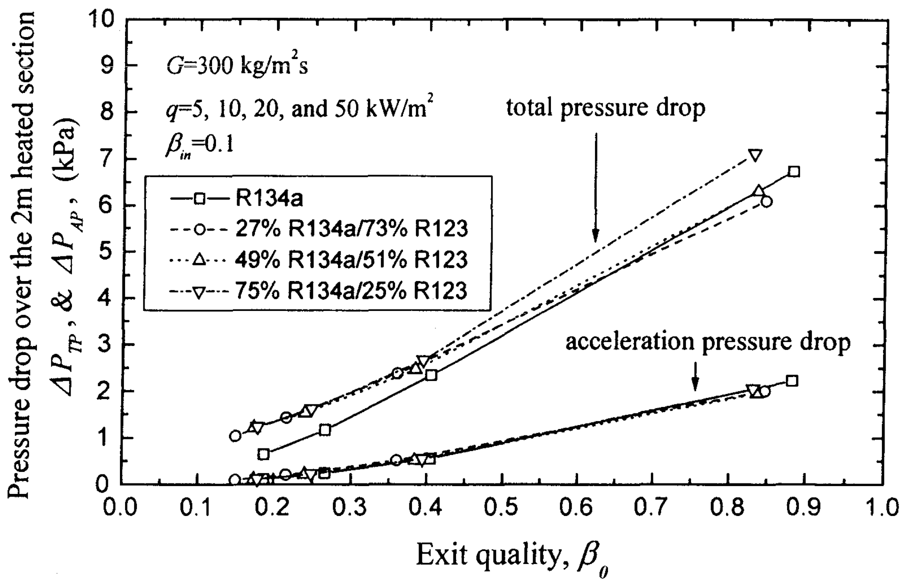


Fig. 9 Variations of the total and acceleration pressure drops as a function of the exit quality

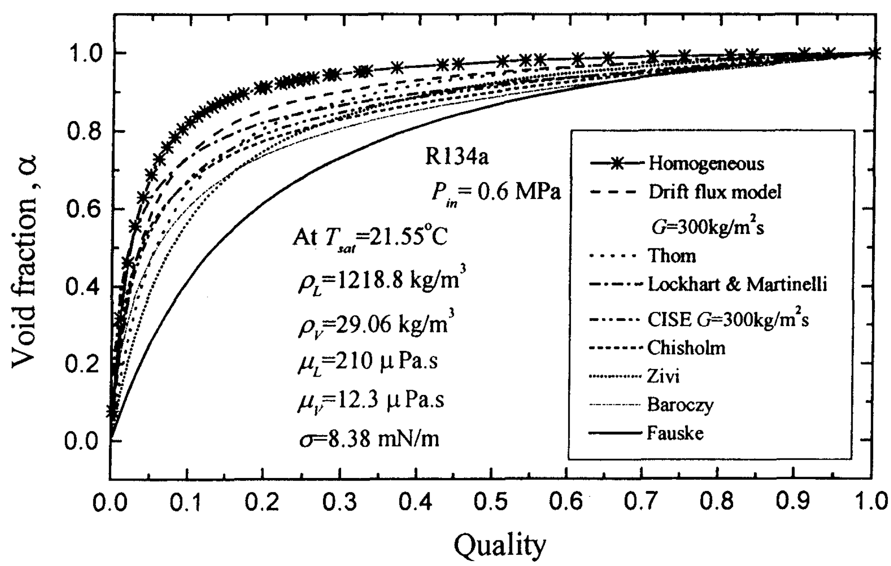


Fig.10 Variations of the void fraction predicted from various correlations

Here the void fraction α is calculated using CISE[9] correlation although there is a wide deviation between various correlations of void fraction as illustrated in **Figure 10**. As shown in the figure, the acceleration pressure drop is not significant at low quality. As quality is increased, the acceleration pressure drop accounts for approximately 30 percent of the total pressure drop.

Figure 11 compared the measured frictional pressure drop for pure refrigerants and their mixture and those calculated using the correlations of Friedel. In the same way as in the adiabatic flow condition, Friedel correlation overpredicted the present data in the stratified and stratified-wavy flow region by about 20%, and it underpredicted in the annular flow region by about 20%.

Figure 12 shows the similar comparison between the measured frictional pressure drop and those predicted by the newly proposed multiplier in this study. The mean deviation for pure refrigerants R134a and R123 and their mixture are found as 23.7, 29.7, and 17.1%,

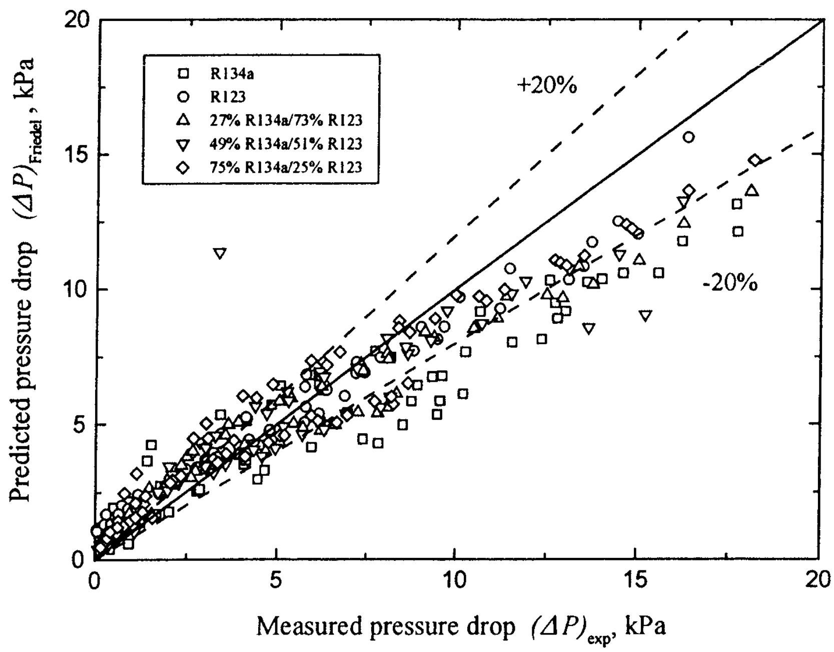


Fig.11 Comparison between measured data and the predicted frictional pressure drop from Friedel correlation

Table 1 Comparison of the percentage deviation between the several correlations and the present data.

Refrigerants	Martinelli. & Nelson Mean	& Ave.	Friedel Mean	& Ave.	Chisholm Mean	& Ave.	This study Mean	& Ave.
27%R134a/73%R123	66.6	6.5	33.9	18.9	31.2	1.4	10.4	5.5
49%R134a/51%R123	82.1	81.1	46.5	32.3	40.7	14.1	24.5	14.1
75%R134a/25%R123	64.9	64.7	43.7	31.5	34.5	4.4	16.3	13.3
R134a	52.2	46.6	38.1	4.5	43.3	-5.9	23.7	6.4
R123	95.8	95.8	47.2	37.8	47.9	13.8	29.7	23.3

(Mean: mean deviation, Ave.: average deviation)

respectively. **Table 1** lists the mean deviation and the average deviation that a few correlations indicate for the present data.

4. Conclusions

An experimental study on the two-phase frictional pressure drop during flow boiling of pure refrigerants R134a and R123, and their mixture was performed in a uniformly heated horizontal tube. Based on the measured data, the following conclusions were reached.

1. In an adiabatic experiment, it was seen that the measured frictional pressure drop increases in an S-shaped curve as quality is increased. Because the existing correlations were quite different with this variation, none of them satisfy the present data.
2. Friedel correlation predicted well the frictional pressure drop for both pure refrigerants and their mixture, but it overpredicted the present data in the stratified and stratified-

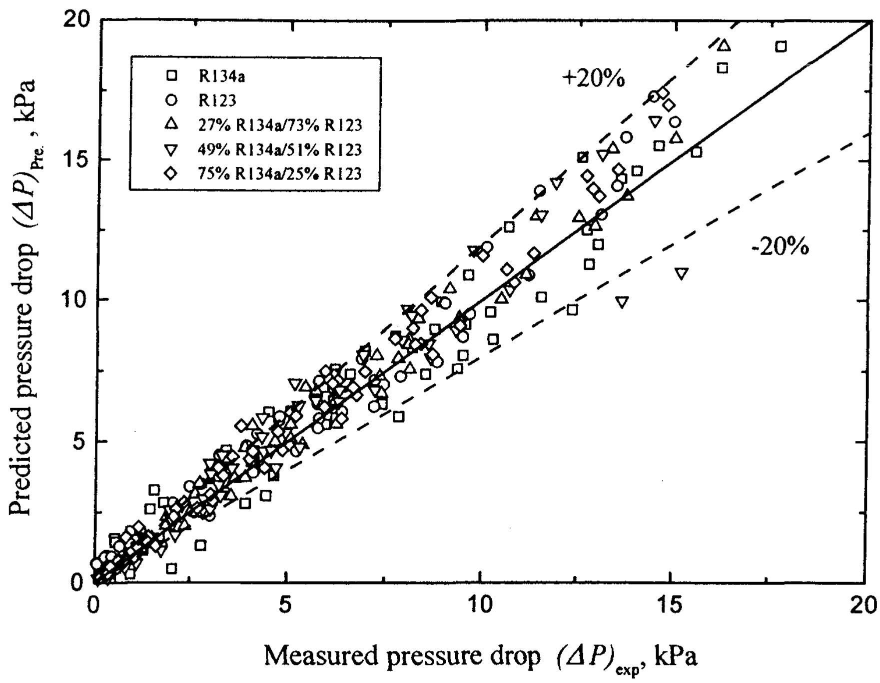


Fig.12 Comparison between measured and the predicted frictional pressure drops from a new correlation

wavy flow region, and underpredicted in the annular flow region, for the increase of the *S*-curve type obtained in the present study.

3. Accordingly, the two-phase frictional multiplier with the increase of the *S*-shaped curve was developed using non-dimension parameters such as Fr_{TP}, We_{TP} and X_{tt} by considering physical properties, mass flux and two-phase effects.
4. In a diabatic experiment, no particular difference between pure refrigerants and mixtures with composition was found in the pressure drop of the two-phase flow boiling. The acceleration pressure drop was not very significant at low quality, but accounted for approximately 30 percent of total pressure drop at high quality.
5. In appling the two-phase multiplier developed in an adiabatic condition to the data obtained in a diabatic, the integration averaged two-phase multiplier was found to correlate most of the data for both pure refrigerants R134a and R123, and their mixture almost with a mean deviation of 20%.

Nomenclature

D	diameter, m
f	friction factor, $=0.079\text{Re}^{-1/4}$
Fr	Froude number, $=G^2/gD\rho^2$
G	mass flux, kg/m^{2}s
L	tube length
ΔP	pressure drop, kPa
q	heat flux, W/m^2
Re	Reynolds number, $=GD/\mu_l$
X	mole fraction in liquid
Y	mole fraction in vapor
We	Weber number, $=G^2D/\sigma\rho$

z axial distance, m

Greek symbols

α void fraction

β vapor quality

μ viscosity, Pa • s

ρ density, kg/m^3

ϕ two phase frictional multiplier

Subscripts

a acceleration

f frictional

fo total flow assumed as liquid

i inlet of the heat transfer section

l liquid

o exit of the heat transfer section

TP two phase

v vapor

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