Pressure Drop in Two-Phase Flow Boiling of R134a, R123 and Their Mixture in Horizontal Tube

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Key words: Acceleration pressure drop, Frictional pressure drop, Pure refrigerant, Two-phase flow boiling

ABSTRACT: An experimental study on the pressure drop during flow boiling for pure refrigerants R134a and R123, and their mixture was carried out in a uniformly heated horizontal tube. Tests were run at a pressure of 0.6 MPa and in the ranges of heat flux 5~50 kW/m^2, vapor quality 0~100 percent and mass velocity of 150~600 kg/m^{2}s. Generally, the two-phase frictional multiplier is used to predict the frictional pressure drop during the two-phase flow boiling. The obtained results have been compared to the existing various correlations for the two-phase multiplier. Also, the frictional pressure drop was compared to a few available correlations; The Lockhart-Martinelli correlation considerally overpredicted the frictional pressure drop data for mixture as well as pure components in the entire mass velocity ranges employed in the present study, while the Chisholm correlation underpredicted the present data. The Friedel correlation was found to satisfactorily correlate the frictional pressure drop data except for a low quality region.

Nomenclature

d : tube inner diameter [m]
f : friction factor
Fr : Froude number
G : mass velocity [kg/m^{2}s]
L : tube length [m]
ΔP : pressure drop [Pa]
Pr : Prandtl number
Re : Reynolds number
s : slip ratio
T : temperature [K]
We : Weber number
X_{tt} : Martinelli parameter
z : axial distance [m]

Greek symbols

α : void fraction
β : vapor quality
ρ : density [kg/m^3]
μ : viscosity [Pa·s]
ϕ : two-phase frictional multiplier

Subscripts

a : acceleration
f : fluid
F : frictional
fo : total flow assumed as liquid
TP : two-phase
v : vapor

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1. Introduction

In the past, experimental studies and empirical and predictive methods were carried out for two-phase pressure drop in tubes, which is an essential element for the design of efficient heat exchanger such as refrigeration and air-conditioning systems. As a result of these efforts, several 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 during two-phase flow boiling consists of the sum of two components, that is, frictional pressure drop and pressure drop due to acceleration. The frictional pressure drop is the most difficult component to predict, and makes the most important contribution to the total pressure drop. On the other hand, the acceleration pressure drop resulting from the variation of the momentum flux caused by phase change is generally small as compared to the frictional pressure drop. The frictional pressure drop during flow boiling is predicted by using two ways: the homogeneous model[(1)] assuming equal phasic velocities and the separate model referred to as a slip flow model.

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. Pierre[(2)] employed the homogeneous model to developed a correlation from the measured pressure drop data with refrigerants R12, R22 and R502. Lockhart and Martinelli[(3)] originated the separate model and proposed their famous correlating method, which was later modified by Martinelli and Nelson[(4)] to predict the pressure drop in horizontal flow boiling. Jung et al.[(5)] 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 Nelsons correlation. The correlation showed a mean deviation of 8.4% in predicting their data.

The objectives of the present study are to obtain the experimental data for pressure drop during flow boiling in horizontal tube with pure refrigerants R134a, R123 and their mixtures. From the result obtained in this study, we are to elucidate pressure drop characteristics with respect to vapor quality and mass velocity using the two-phase frictional multiplier, and to compare the present data with existing various correlations for pressure drop.

2. Experimental apparatus and procedure

The experimental apparatus used in the present study is schematically shown in Fig. 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 pre-

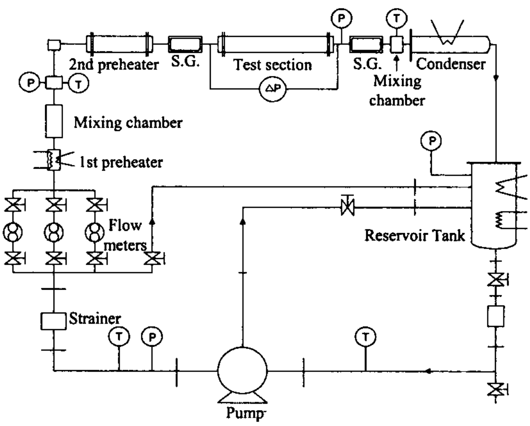


Fig. 1 Schematic of experimental apparatus.

heater to the inlet mixing chamber where fluid temperature and pressure are measured. Then the fluid is heated in the 2^{nd} preheater up to a prescribed enthalpy or vapor quality and then enters the heated test section where the fluid evaporates inside 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. Visual observations were conducted with the high-speed camera through the sight glass tube downstream of the heated section. The images recorded were replayed by the slow motion so as to make the flow patterns discriminated clearly.

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. Electric heating is allowed so as to supply a constant heat flux to the fluid flowing inside the tube along a fixed tube length of 2 m. Also, a desired quality at the inlet of the test section can be obtained by adjusting heat supply at the 2^{nd} preheater. 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.

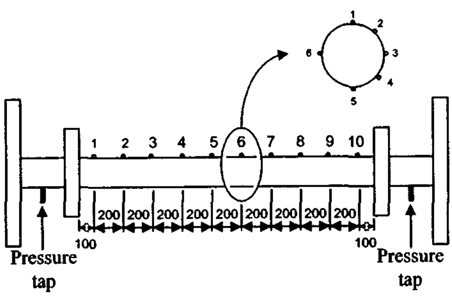


Fig. 2 Detail of test section.

The fluid temperature and pressure are measured in the mixing chambers at the inlet and exit of the test section. The pressure drop between the inlet and exit of the teat section are measured using differential pressure transducer. The pressure taps are closely installed to the heated section, and connected to the pressure transducer. These data of fluid temperature and pressure are used to determine the local fluid temperature and pressure along the test section.

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. Thermodynamic properties of pure refrigerants and their mixtures were calculated using the modified Benedict-Webb-Rubin equation of state with fifteen constant,[6] and transport properties using the method recommended by Reid et al.[7] In the present experiment, the mass velocity 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.

3. Calculation of the total pressure drop

3.1 Theoretical study

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

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

where ΔP_f is the frictional pressure drop and ΔP_a is the acceleration pressure drop.

Generally, the two-phase frictional multiplier is used to predict the frictional pressure drop during the two-phase flow boiling, and can be represented as

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

where ΔP_{TP} is the measured two-phase frictional pressure drop and ΔP_{fo} is the frictional pressure drop if the flow through the horizontal tube is all 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

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

As mentioned above, there are two physical models referred by many researchers when analyzing the pressure drop in flow boiling. They are the separate flow model and the homogeneous model. Correlations based on the separate flow model tend to overestimate the pressure drop, while correlations based on the homogeneous model underpredict the pressure drop in flow boiling of single-component fluids.

The two-phase frictional multiplier is commonly employed to predict the frictional pressure drop during the two-phase flow boiling. Its definition on several available correlations will be briefly explained here.

The homogeneous model is one of the simplest correlations for calculating the two-phase frictional pressure drop, and which is applied by regarding the two-phase flow as a single phase possessing mixture properties, and then the two-phase frictional multiplier is given by

$$\phi_{fo}^2 = \left[1+\beta\left(\frac{\rho_f}{\rho_g}-1\right)\right]\left[1+\beta\left(\frac{\mu_f}{\mu_g}-1\right)\right]^{-1/4} \tag{5}$$

The Lockhart-Martinelli correlation is given as

$$\phi_{fo}^2 = \phi_f^2 (1-\beta)^{1.75} \tag{6}$$

where ϕ_f^2 is expressed in terms of the Martinelli parameter, X_{tt} during flow boiling of gas-liquid mixture in smooth tubes, as follows

$$\phi_f^2 = 1 + \frac{C}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{7}$$

where the constant C ranges from 5 to 20, depending on whether the flow regime of the liquid and vapor phases are laminar or turbulent, and also on the physical properties. The Martinelli parameter, X_{tt} is the ratio of single-phase frictional pressure drop of liquid to that of gas, and defined as

$$X_{tt}^2 = \frac{\left(\frac{dp}{dz}\right)_{F,L}}{\left(\frac{dp}{dz}\right)_{F,G}} \tag{8}$$

The Martinelli-Nelson correlation has been widely used to predict the pressure drop during horizontal flow boiling. In Eq. (4) ϕ_f^2 is written as[8]

$$\phi_f^2 = \left(1 + \frac{1}{X_{tt}^{0.5}}\right)^2 \tag{9}$$

The Chisholm[9] correlated the two-phase multiplier as a function of Lockhart-Martinelli parameter during flow boiling of gas-liquid mixture in smooth tubes. Later,[10] he transformed the two-phase multiplier of Eq. (7) to the general form of ϕ_{fo}^2 as

$$\Phi_{fo}^2 = 1 + (\Gamma^2 - 1)\{B\beta^{(2-n)/2}(1-\beta)^{(2-n)/2} + \beta^{2-n}\} \tag{10}$$

where the physical property coefficient, Γ and B are defined as

$$\Gamma = \left(\frac{\rho_L}{\rho_G}\right)^{0.5}\left(\frac{\mu_G}{\mu_L}\right)^{n/2} \tag{11}$$

Table 1 Value of B according as Γ for smooth tubes

Γ	G (kg/m^{2}s)	B
	≤ 500	4.8
≤ 9.5	$500 < G < 1900$	$2400/G$
	≥ 1900	$55/G^{0.5}$
$9.5 < \Gamma < 28$	≤ 600	$520/(\Gamma G^{0.5})$
	> 600	$21/\Gamma$
≥ 28		$15000/\Gamma^2 G^{0.5}$

$$B = \frac{C\Gamma - 2^{2-n} + 2}{\Gamma^2 - 1} \qquad (12)$$

In Eqs. (11) and (12), n denotes the exponent in the Blasius equation for friction factor. The value of B is determined with mass flux for the range of the physical property coefficient, Γ, as shown in Table 1.

The Friedel[11] correlation, based on a large experimental data bank, is obtained by optimizing the following equation for the two-phase multiplier assumed as all liquid flow.

$$\phi_{fo}^2 = A + 3.24\beta^{0.78}(1-\beta)^{0.224}\left(\frac{\rho_f}{\rho_v}\right)^{0.91}\left(\frac{\mu_v}{\mu_f}\right)^{0.19} \times\left(1-\frac{\mu_v}{\mu_f}\right)^{0.7} \mathrm{Fr}_{TP}^{-0.0454}\,\mathrm{We}_{TP}^{-0.035} \qquad (13)$$

where,

$$A = (1-\beta)^2 + \beta^2\rho_f f_{go}(\rho_g f_{fo})^{-1}$$

The two-phase Froude and Weber numbers are given, respectively, as

$$\mathrm{Fr}_{TP} = \frac{G^2}{gD\rho_{TP}^2}, \quad \mathrm{We}_{TP} = \frac{G^2 D}{\sigma\rho_{TP}} \qquad (14)$$

Jung et al. modified the correlation of Martinelli and Nelson and expressed the two-phase frictional multiplier as a function of quality and a reduced pressure.

$$\phi_{fo}^2 = 30.78\beta^{1.323}(1-\beta)^{0.477}\,\mathrm{Pr}^{-0.7232} \qquad (15)$$

3.2 Acceleration pressure drop

The acceleration pressure drop under the heated condition is evaluated from the following equation.

$$\Delta P_a = G^2\left[\left\{\frac{\beta^2}{\alpha\rho_v} + \frac{(1-\beta)^2}{(1-\alpha)\rho_f}\right\}_{out} - \left\{\frac{\beta^2}{\alpha\rho_v} + \frac{(1-\beta)^2}{(1-\alpha)\rho_f}\right\}_{in}\right] \qquad (16)$$

Here α denotes the void fraction, which is related to the vapor quality and the slip ratio as

$$\alpha = \frac{1}{1+\left(s\dfrac{1-\beta}{\beta}\dfrac{\rho_v}{\rho_f}\right)} \qquad (17)$$

There are proposed many correlations for the slip ratio. Among them, the following CISE[12] correlation is used to calculate the slip ratio.

$$s = 1 + E_1\left(\frac{y}{1+yE_2} - yE_2\right)^{0.5} \qquad (18)$$

where, y, γ, E_1, and E_2 are

$$y = \frac{\gamma}{1-\gamma}, \qquad \gamma = \frac{\rho_f\beta}{\rho_f\beta + \rho_g(1-\beta)}$$

$$E_1 = 1.578\,\mathrm{Re}^{-0.19}\left(\frac{\rho_f}{\rho_g}\right)^{0.22}$$

$$E_2 = 0.02733\,\mathrm{We}\,\mathrm{Re}^{-0.51}\left(\frac{\rho_f}{\rho_g}\right)^{0.08}$$

Figure 3 shows the slip ratio predicted from various models and correlations for pure refrigerants and mixtures. The Different values of the predicted slip ratio in Fig. 3 result in a deviation of the void fraction calculated from Eq. (17) as shown in Fig. 4. Use of the CISE correlation for slip ratio in this study is owing

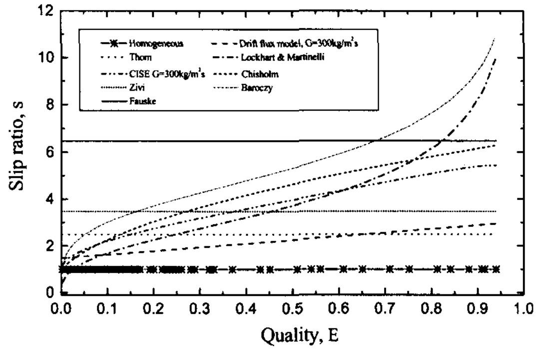


Fig. 3 Variations of slip ratio for various correlations with R134a.

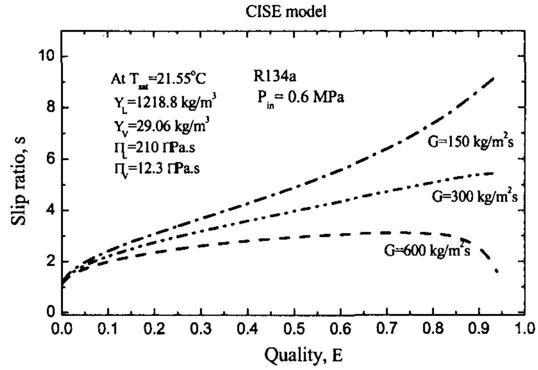


Fig. 5 Variation of slip ratio with respect to mass velocity with R134a.

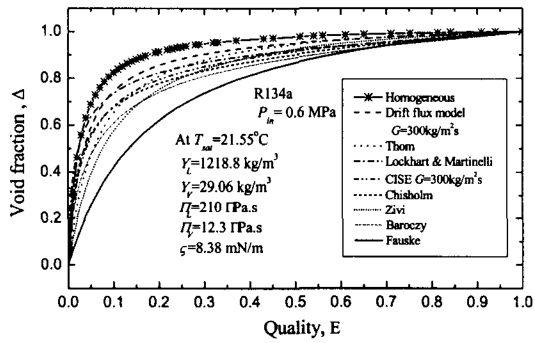


Fig. 4 Variations of the void fraction predicted from various correlations.

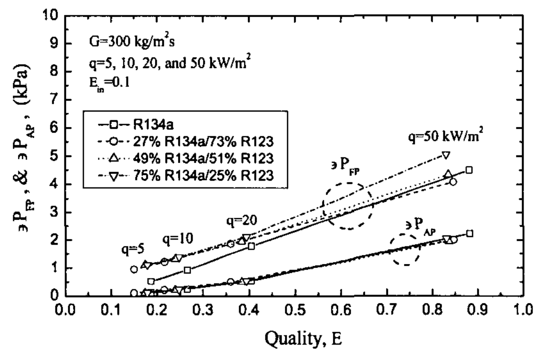


Fig. 6 Variations of the frictional and acceleration pressure drop as a function of exit quality.

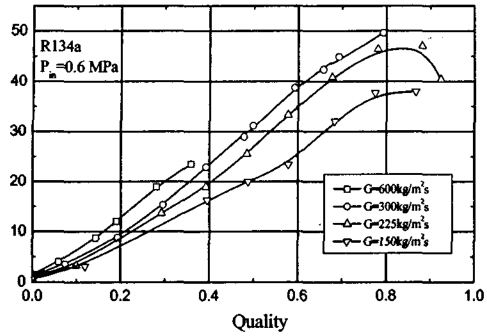
to that it includes the influence of mass velocity and predicted more accurate and moderate slip ratio under various flow conditions, as indicated in Whalley.[13] Figure 5 shows the variation of slip ratio estimated from the CISE model.

Figure 6 depicts the two components of the frictional pressure drop and the acceleration pressure drop, which compose the total pressure drop. Here, the acceleration pressure drop was obtained by subtracting the acceleration pressure drop from the measured total pressure drop. The acceleration pressure drop is not very significant at lower quality. As quality is increased, however, the acceleration pressure drop accounts for approximately 30 percent of the total pressure drop.

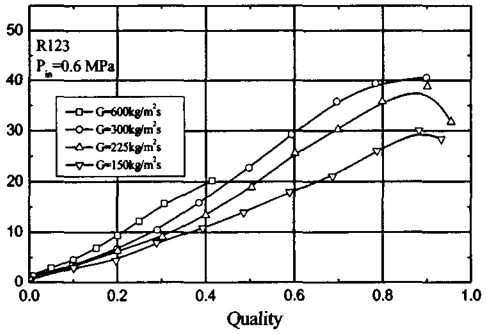
4. Results and discussion

Figure 7 shows the variations of the two-phase frictional multipliers calculated from the measured frictional pressure drops using Eq. (2). As shown in Fig. 7, the pressure drop increases with an increase in vapor quality and mass flux. Vapor quality and mass flux dependency of frictional pressure drop 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.

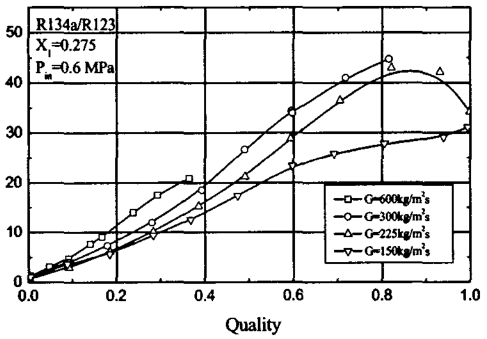
Figure 8 shows the comparison between the measured two-phase multiplier and several typical correlations. As shown in the Fig. 8, these results were compared correlations vary quite



(a) Pure refrigerant, R134a



(b) Pure refrigerant, R123

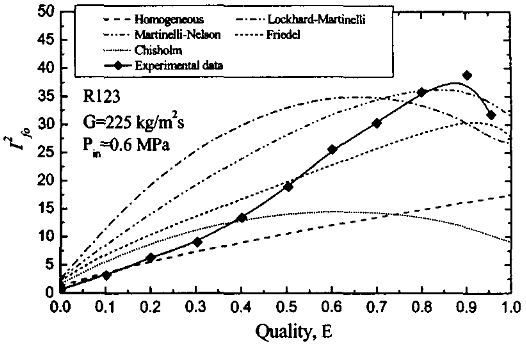


(c) Mixture

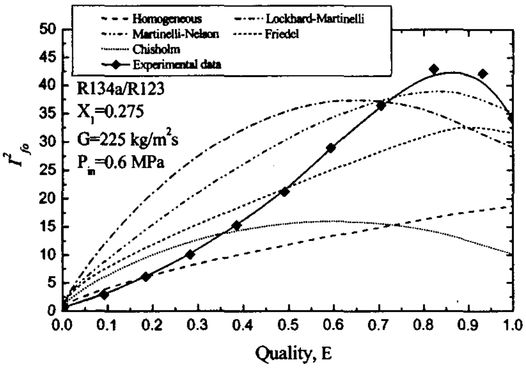
Fig. 7 Variations of the two-phase frictional multipliers against quality.

widely. The homogeneous flow model shows the much smaller value than other correlations.

The Friedel correlation lies to the middle of other correlations with a nearly linear variation, whereas the Lockhart-Martinelli and Martinelli-Nelson correlations show the larger value with a non-leaner variation as compared with other



(a) R123

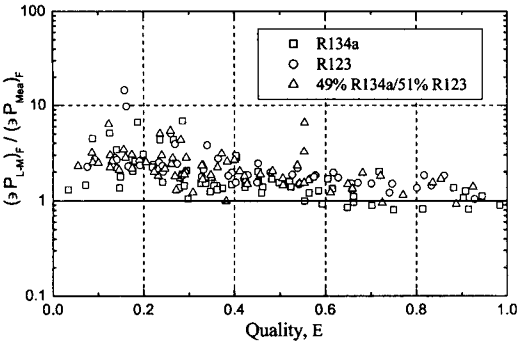


(b) Mixture

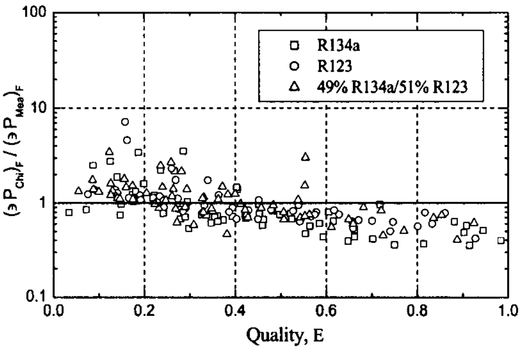
Fig. 8 Comparison between the measured frictional multiplier and several correlations.

correlations. Consequently, It is found from the Fig. 8 that none of the existing correlations satisfy the present data.

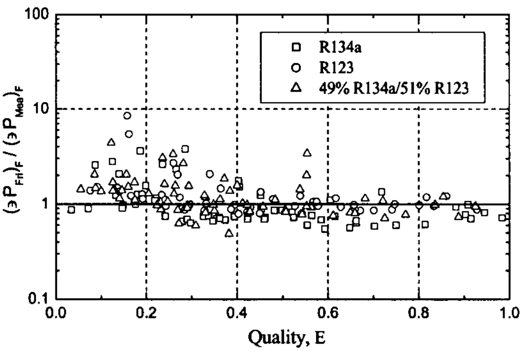
Figure 9 indicates the comparisons between the measured frictional pressure drop for pure refrigerants and their mixtures and those calculated using the correlations of Lockhart & Martinelli, Chisholm, and Friedel. Lockhart & Martinelli correlation overpredicted the frictional pressure drop for mixtures as well as pure refrigerants in the entire mass flux ranges employed in this study. On the other hand, Chisholm correlation underpredicted the present data for the entire range of mass flux and quality. Friedel correlation satisfactorily predicted the present data at higher quality except for lower quality region ($\beta < 0.2$).



(a) Lockhard-Martinelli correlation



(b) Chisholm correlation



(c) Friedel correlation

Fig. 9 Comparisons between measured data and several correlations.

5. Conclusions

An experimental result on the two-phase frictional pressure drop during flow boiling of pure refrigerants R134a and R123, and their mixtures increased with an increase in vapor quality and mass velocity. It was found that the variation of pressure drop, as the inlet quality is increased, had a similar pattern for both pure refrigerants and their mixture. The acceleration pressure drop was not significant at low quality, but accounted for approximately 30 percent of the total pressure drop at high quality. Lockhart & Martinelli correlation over-predicted the frictional pressure drop for the entire range of mass flux and quality employed in this study. Chisholm correlation, on the other hand, underpredicted the present data. Friedel correlation satisfactorily predicted the frictional pressure drop for both pure refrigerants and their mixture, but it somewhat overpredicted the present data at lower quality region ($\beta < 0.2$).

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