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

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Two-Phase flow pattern and pressure drop data were obtained for pure refrigerants R134a and R123 and their mixtures as test fluids in a horizontal tube. The flow pattern is observed through tubular sight glasses located at inlet and outlet of the test section. The flow map of Baker developed for air-water two-phase flow at atmospheric pressure failed to predict the observed flow patterns at the higher value of the mass velocity used in the present study. The map of Kattan et al. predicted the data well over the entire region of mass velocity selected in the present study. The measured pressure drop increased with an increase in vapor quality and mass velocity. A new two-phase multiplier was developed from a dimensional analysis of the frictional pressure drop data measured in the present experiment. This new multiplier was found successfully to correlate the frictional pressure drop.

Key Words : Flow Pattern Map, Pressure Drop, Multiplier

Nomenclature

D	Diameter [m]
f	Friction factor
g	Acceleration due to gravity [m/s^2]
G	Mass velocity [kg/m^{2}s]
Fr	Liquid Froude number
L	Tube length [m]
P	Pressure drop [Pa]
Re	Reynolds number
x	Vapor quality
X_{tt}	Martinelli parameter in Eq. (8)
We	Weber number

Greek symbols

μ	Viscosity [Pas]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]
ϕ	Two-phase frictional multiplier

Subscripts

a	Acceleration
f	Frictional
fo	Total flow assumed as liquid
l	Liquid
TP	Two phase
v	Vapor

1. Introduction

Several flow pattern maps have been proposed for two-phase flows in horizontal tubes. Flow patterns during two phase flow boiling are influenced by several factors, that is, gravity, vapor shear, and surface tension forces. The gravity forces are often dominant over the stratified and wavy flow at low mass velocities. The vapor shear forces are dominant over the annular flow at high mass velocities. The surface tension force can be important in small tubes as indicated by Wambsganss et al. (1991). The transition of a certain flow pattern to another was found to influence the pressure drop as confirmed in Wang et al. (1997). As indicated in Hosler (1968), identifying the flow pattern in two-phase flow is very

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important analogously to knowing whether the flow is turbulent or laminar in single-phase flow. This is because the pressure drop is closely related to the prevailing flow pattern.

The Baker (1954) developed the map for air-water two-phase flow at atmospheric pressure. Six flow patterns are identified on the map having the coordinates of the superficial mass velocity of gas versus the superficial mass velocity of liquid. The Baker map failed to predict the observed flow patterns at the higher value of the mass velocity used in the present study.

The Kattan et al.(1995b) modified the VDI (1993) flow pattern map and developed a new flow map valid for both adiabatic and diabatic flows in horizontal tubes, based on flow pattern data for five different refrigerants covering a wide range of mass velocity and vapor quality.

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 in boiling two-phase flow consists of two components, frictional pressure drop and acceleration pressure drop. The frictional pressure drop usually makes a main contribution to the total pressure drop while its precise predictions not easy. On the other hand, the acceleration 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.

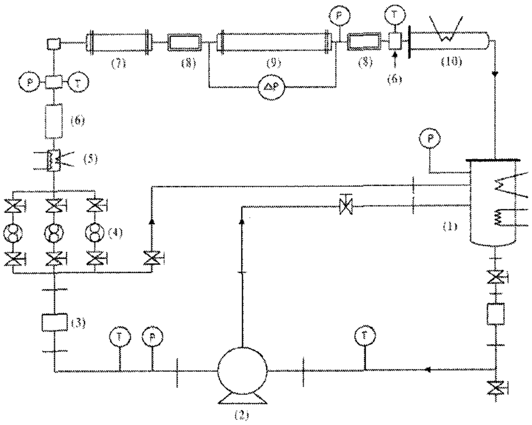
There are two physical models referred by many researchers when analyzing the pressure drop in flow boiling. They are the separate flow model and the homogeneous model (Collier and Thome, 1994). Two models are used in many cases to predict the frictional pressure drop in flow boiling: the homogeneous model that assumes equal phase velocity and the separate flow model that allows a slip velocity between two phases.

Based on a large experimental data bank, Friedel (1979) obtained the two-phase multiplier both for horizontal (and, vertical upward) flow and vertical downward flow. Friedel correlation was found to predict the present data very well for the two-component data although originally derived based on single-component two-phase flow data.

The object of the present study is first 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. Based on the visual observations, secondly, the relationship between the flow pattern and pressure drop will be made clear and an assessment of available correlations for the flow pattern map will be done. Finally, a new correlation for the pressure drop is developed to reproduce the present data with reasonable accuracy.

2. Experimental Apparatus and Procedure

Figure 1 schematically shows the experimental apparatus consisting of a reservoir tank, pump, flow meters, mixing chambers, preheaters, sight glass sections, the test section, condenser and other accessories.



(1) Reservoir Tank (2) Pump (3) Straince (4) Flow meters (5) 1st preheater (6) Mixing chamber (7) 2nd preheater (8) Sight glass (9) Test section (10) Condenser

Fig. 1 Experi,ental apparatus

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. 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 2nd 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.

At the inlet and exit of the test section, the fluid temperature and pressure in the mixing chambers are measured. 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.

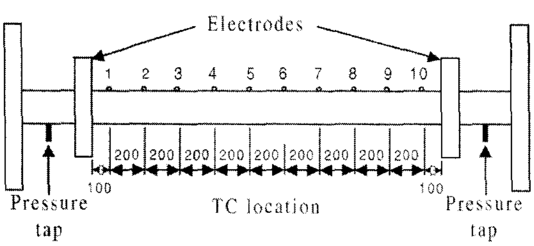


Fig. 2 Detail of test section

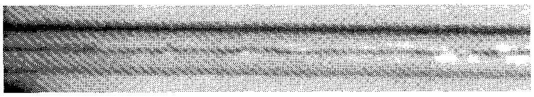
Refrigerants R134a and R123 are selected as test fluids of pure components. They are respectively mixed as the more- and less-volatile components to constitute binary mixtures. Thermodynamic properties of pure refrigerants and their mixtures were calculated using the modified Benedict-Webb-Rubin equation of state with fifteen constant (1977), and transport properties using the method recommended by Reid et al. (1977). 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. Flow Pattern

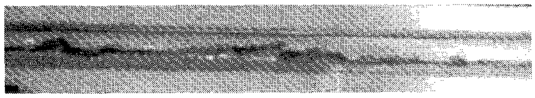
Figure 3 shows typical pictures of the observed flow patterns with the high-speed camera. Observed flow patterns are classified into some basic situations as follows.

(1) Plug flow : Bubbles begin to grow on the tube wall, and gradually become vigorous.

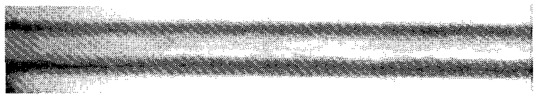
(a) Intermittent flow



(b) Stratified flow

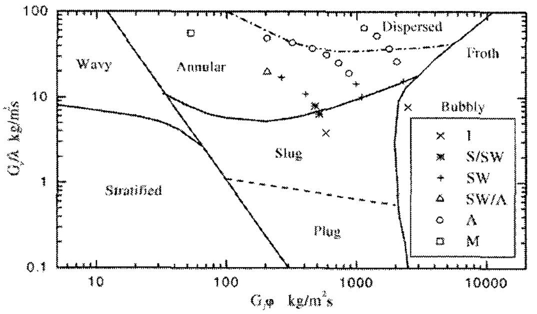


(c) Stratified-wavy flow

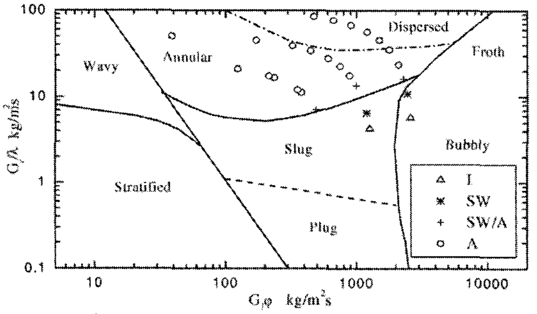


(d) Annular flow

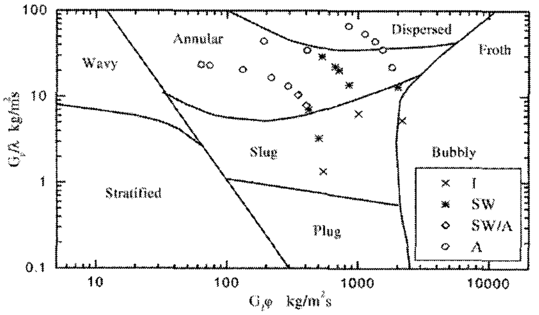
Fig. 3 Typical pictures of flow patterns



(a) R-134a



(b) R-123



(c) Mixture

Fig. 4 Comparison between the observed and Baker flow pattern map

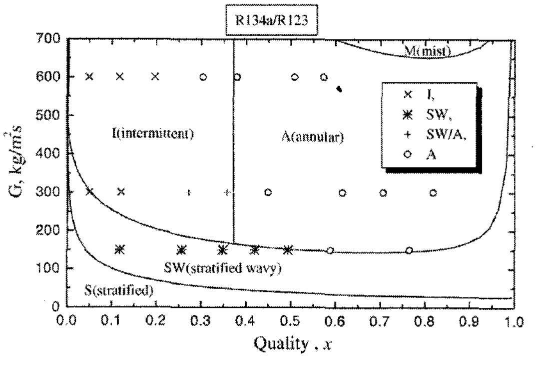


Fig. 5 Comparison between the observed and Kattan et al. flow pattern map

(2) Slug flow : Vapor bubbles grown as a big lump flow as the slug concentrated near the top of the tube.

(3) Stratified flow : Vapor and liquid phases flow separately with the upper and lower part of a horizontal tube, respectively.

(4) Wavy flow : The interface between two phases was disrupted by waves. In the disrupted interface, the entrainment of liquid droplets occurs from the liquid film to the vapor.

(5) Annular flow : Liquid phase flows in the form of liquid film around the tube periphery, and vapor in the central core. The distribution of the liquid film circumferentially is thicker at the bottom of the tube than at the top due to gravity.

(6) Mist flow : The flow is the continuous flow of the vapor phase.

Figure 4 shows the Baker flow pattern map. It was seen from the Figure that the Baker map failed to predict the observed flow patterns at higher value of the mass velocity used in the present study. This is because the flow pattern maps developed in the air-water system is not applicable to liquid and vapor systems.

Figure 5 shows the flow pattern map of Kattan et al. who plotted the flow pattern data on the mass velocity versus quality coordinates. They modified the VDI 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 velocity and vapor quality. A significant feature of the map is easy to distinguish the transition qualities from one flow pattern to another. As seen in Fig. 5 the present data for mixtures are predicted well by the flow pattern map of Kattan et al. According to the result observed in this study, the transition quality to annular flow was shown to be gradually getting smaller as the mass velocity was increased.

4. Pressure Drop

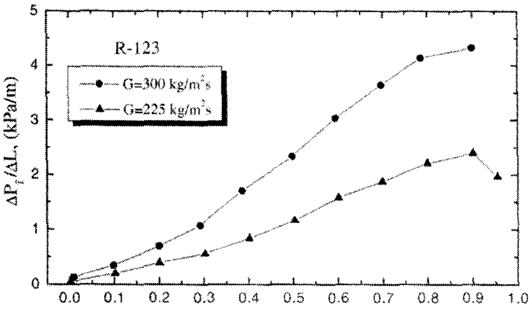
The measured total pressure drop during two-phase flow boiling in a horizontal tube consists of two components as given by

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

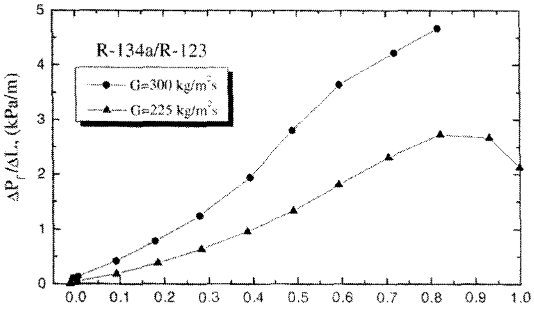
where ΔP_f is the frictional pressure drop and ΔP_a is the acceleration pressure drop. As mentioned above, the frictional pressure drop is the most difficult component to predict, and makes the most important contribution to the total pressure drop. On the other hand, the acceleration pressure drop resulting from the variation of the momentum flux caused by phase change is generally small as compared to the frictional pressure drop. Here, 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.

Figure 6 indicates, as a function of quality, the frictional pressure gradient measured over the pressure taps under the adiabatic condition. It is seen from the figure that the pressure drop increases with an increase in vapor quality and mass velocity. Vapor quality and mass velocity 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.

Figure 7 shows each of the flow region indicated on the variation of the pressure gradient with vapor quality according to the result of Fig. 5. As shown in Fig. 7, it is found that the transition from stratified-wavy or stratified-wavy/annular to annular flow for mixture occurs at approximately quality of 0.4. This agrees with two-phase flow pattern data observed in this study. In this study, the transition quality to an annular flow has been shown that different with that of other investigations which occur at the quality range from 0.15 to 0.25. Among them, Jung et al. (1989) observed an annular flow pat-

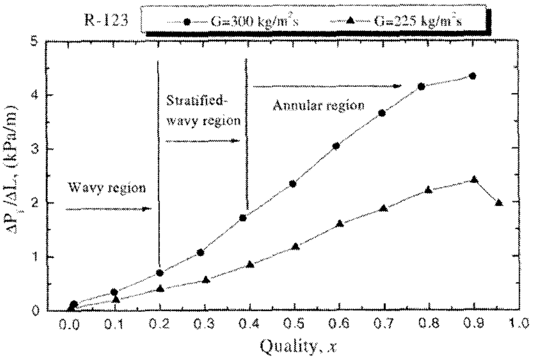


(a) R-123

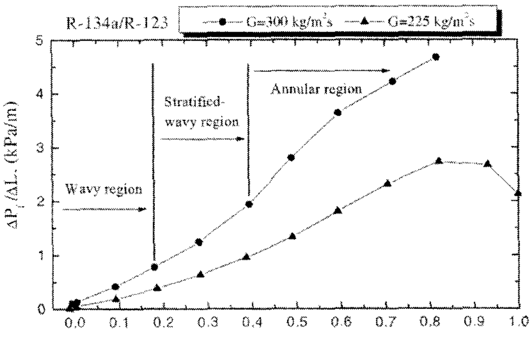


(b) Mixture

Fig. 6 Variations of pressure gradient against quality



(a) R-123



(b) Mixture

Fig. 7 Comparison between flow pattern and pressure gradient tern since quality is over 0.2. The pure component of Fig. 7(a), is a little more easy to distinguish the transition for each region as compared to mixture transformed smoothly during the transition, and it can be said that the region of quality around 0.3 is put at a state in a period of transition towards annular flow. Namely, the information on the transition of the flow pattern can be confirmed from the measured pressure drop data during two-phase flow boiling in horizontal tube. However, the distinction between each of the flow region was not clearly made in the two-phase pressure gradient. Two-phase pressure drop or pressure gradient are often expressed in terms of a two-phase multiplier. Thus the multiplier is defined as

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

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

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

Here the friction factor for turbulent flow is given as

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

Figure 8 shows the comparison between the measured two-phase multiplier and Friedel correlation. The correlation of Friedel relatively overpredicted the present data for both pure refrigerants and their mixture at low quality, and underpredicted at high quality. The present data located in a downside than Friedel correlation correspond to the stratified and stratified-wavy flow region. Those in upside, on the other hand, correspond to the annular flow region. The entrainment of liquid droplets due to an interaction between two-phase vigorously occurs in the transition process from the stratified-wavy flow to annular flow. From the flow patterns observed, the entrainment of liquid droplets from the liquid film to the vapor core is easily observed in the distrupted interface of stratified-wavy and annular flow. As mass velocity is increased, this liquid entrainment strongly occurrs at the interface, and also it causes partial dryout at the top in the high quality region.

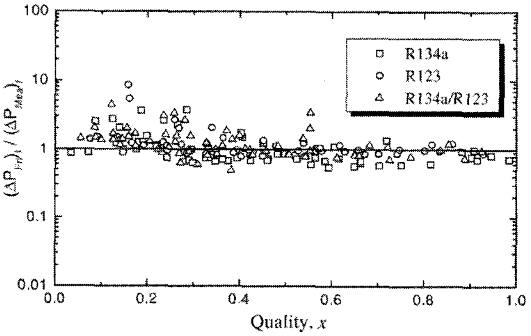


Fig. 8 Comparison between measured data and Friedel correlation

Accordingly, the two-phase frictional multiplier data obtained in this study can be correlated based on the Friedel correlation. The two-phase multiplier, namely, is a function of non-dimension parameters such as Fr_{TP} and We_{TP} and the Martinelli parameter X_{tt}.

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

where Fr_{TP} and We_{TP} denote the two-phase Froude and Weber number, and are defined, respectively, as

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

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

Here ρ_{TP} is the homogeneous density defined as

$$\rho_{TP}=\left[\frac{x}{\rho_v}+\frac{1-x}{\rho_l}\right]^{-1} \tag{8}$$

X_{tt} is the Martinelli parameter.

$$X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{9}$$

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

$$\phi_{fo}^2=1.7+\frac{(6.3+Fr_{TP})^{0.89}}{(1.04Fr_{TP}^{0.52}\cdot We_{TP}^{-0.011})}\left(\frac{1}{X_{tt}}\right)^{0.42} \tag{10}$$

Figure 9 indicates the comparison between the measured frictional pressure drop and that calculated using Eq. (10). It is found from the Figure that the two-phase multiplier proposed in

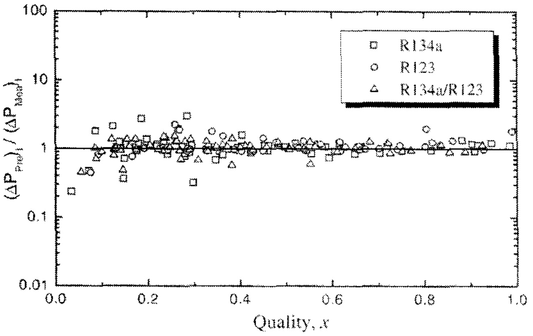


Fig. 9 Comparison between measured and predicted pressure drop

the present study satisfactorily predicts the present data for the entire region of quality within a mean deviation of 20%.

5. Conclusions

Flow pattern and pressure drop during two-phase flow boiling were measured for pure refrigerants R-134a and R-123, and their mixture in a uniformly heated horizontal tube. Based on the measured data, The conclusions are summarized as follows.

(1) From visual observations the obtained flow pattern data were predicted well by Kattan map. The flow pattern map of Kattan et al., however, failed to predict the transition quality to annular flow at higher mass velocity,

(2) The measured pressure drop increases with an increase in vapor quality and mass velocity. By showing each of the flow region on the pressure gradient, it was confirmed that the flow pattern have closely relation to the pressure drop.

(3) Friedel correlation predicted well the present data for the frictional pressure drop for both pure refrigerants and their mixture at high quality, but it failed to correlate the pressure drop data in the stratified-wavy flow region, that is, at low quality.

(4) The frictional pressure drop calculated with the two-phase multiplier proposed in present study was found to correlate most of the data for both pure refrigerants and their mixture within a mean deviation of 20%.

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