Prediction of the Transition Criterion to Annular Flow in Two-Phase Flow Pattern of Refrigerants*

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Two-phase flow pattern data during horizontal in-tube flow boiling are presented for pure and mixed refrigerants of R134a and R123. The flow pattern is observed through tubular sight glasses located at inlet and outlet of the test section, which is made of a stainless steel tube, 2 m long with 10 mm I.D., 1.5 mm wall thickness. The obtained results are compared to the available various correlations for flow pattern. The flow pattern map of Hashizume was very well agreement with the present data except the region of low mass velocity. Weisman flow pattern map was also known to satisfactorily predict data for refrigerants in the region of annular flow. In order to establish the transition quality to annular flow in this study, flow pattern are simply classified into two groups; stratified (including intermittent, stratified and stratified-wavy) flow and unstratified (annular) flow. The transition quality from stratified to unstratified flow was obtained by modifying the liquid Froude number.

Key Words: Intermittent Flow, Stratified Flow, Stratified-Wavy Flow, Annular Flow, Two-Phase Flow Pattern Map

1. Introduction

Flow patterns during flow boiling in horizontal tubes are influenced by several factors such as the 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.⁽¹⁾ The transition of a certain flow pattern to another was found to influence the pressure drop as confirmed in Wang et al.⁽²⁾ As suggested in Hosler⁽³⁾, identifying the flow pattern in two-phase flow is very 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.

One of the most widely used flow pattern maps for horizontal flow is Baker's map⁽⁴⁾. Baker developed this 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. Scott⁽⁵⁾ subsequently modified it by introducing correction factors to the coordinates so as to apply the map to any other fluids of different pressures.

Hashizume⁽⁶⁾ correlated the experimental data for R12 and R22 obtained in a horizontal tube with a diameter of 10 mm. He regarded the influence of surface tension in the Baker map as too large, and modified the property correction term to a suitable form to refrigerants.

The flow pattern map of Weisman et al.⁽⁷⁾ was developed for horizontal tubes with diameters in the range of 0.012 to 0.051 m during co-current gas liquid flow. They used a map based on plotting superficial liquid velocity vs superficial gas velocity. Through systematic studies on the effects of liquid viscosity, liquid and gas density, surface tension, and tube diameter, they proposed the different four transition crite-

* Received 30th August, 2002 (No. 02-5130)

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rions for flow patterns.

Kattan et al.⁽⁸⁾ modified the VDI⁽⁹⁾ 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.

The objectives of the present study are to obtain the experimental data for flow pattern during flow boiling in horizontal tube with pure refrigerants R134a and R123 and their mixtures and to compare the measured data to the existing various correlations. Finally, the liquid Froude number, to predict the transition quality to annular flow, is corrected as a function of the vapor quality.

Nomenclature

- g : acceleration due to gravity [m/s^2]
 G : mass velocity [$\text{kg/m}^2\text{s}$]
 Fr_L : liquid Froude number
 V_G^s : superficial gas velocity [m/s]
 V_L^s : superficial liquid velocity [m/s]
 C_{FrL} : factor defined in Eq. (2)
 Greek symbols
 χ : vapor quality
 ρ : density [kg/m^3]
 λ : property correction factor used in Fig. 3
 ψ : property correction factor used in Fig. 3
 Subscripts
 L : liquid
 G : gas
 o : outlet

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 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 (under the constant system pressure of 0.6 MPa) can be obtained by adjusting heat supply at the 2nd pre-heater.

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

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

Fig. 1 Experimental apparatus

Fig. 2 Detail of test section

differential pressure transducers. 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⁽¹⁰⁾, and transport properties using the method recommended by

Fig. 3 Typical pictures of flow patterns for R134a

Fig. 4 Typical pictures of flow patterns for Mixture ($X_1=0.49$)

Reid et al.⁽¹¹⁾ In the present experiment, the mass velocity is set at 150, 225, 300 and 600 kg/m²s, and heat flux is varied at 5, 10, 20 and 50 kW/m². Vapor quality covers zero to almost unity.

3. Flow Pattern

3.1 Flow pattern classification

Flow patterns encountered in the present experiments are classified into some basic situations as follows;

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

(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.

3.2 Flow pattern observation

Figures 3 and 4 show typical pictures of the observed flow patterns with the high-speed camera for mass velocity from 150 to 600 kg/m²s. It is seen from the figure that the flow patterns for $G=150$ kg/m²s includes the intermittent (including the plug and slug), stratified and stratified-wavy flow pattern. For the mass velocity of 150 kg/m²s, the annular flow pattern was hardly observed in quality less than 0.6. In a quality over 0.6, it was very difficult to distinguish whether the flow pattern is annular or not. The flow pattern for $G=300$ kg/m²s exhibited the intermittent, stratified, stratified-wavy and annular flow. For $G=150$ kg/m²s in this study, the transition from the stratified-wavy to annular flow occurred approximately at the quality range of 0.35–0.45. The flow pattern for $G=600$ kg/m²s includes the intermittent, stratified-wavy and annular flow as exhibited in the mass velocity of 300 kg/m²s. Compared to $G=300$ kg/m²s having the transition quality of 0.4, the transition for $G=600$ kg/m²s occurred at 0.15 or 0.2 quality.

4. Results and Discussion

The observed flow patterns were compared to available flow pattern maps, namely the maps of

Hashizume, Weisman et al. and Kattan et al.

Figure 5 indicates the comparisons between the observed flow patterns and Hashizume map. It is found from the figure that the transition boundaries on Hashizume map are very different from those on the Baker map. The Hashizume flow pattern map predicted rather well over the entire flow region, including the intermittent, stratified-wavy and annular flow. His map, however, failed to predict the present data for $G=150$ kg/m²s because he conducted the experiment on two-phase flow of refrigerant for $G>300$ kg/m²s. From the boundary on Hashizume map, it is found that the transition to annular flow occurs at mass velocity over 150 kg/m²s.

Figure 6 shows the flow pattern map of Weisman et al., which is known to satisfactorily predict data for refrigerants though it was developed for co-current gas liquid flow. It, however, is impossible to predict the observed flow patterns (that is, stratified or wavy flow) in the present experiment except for annular flow.

Figure 7 shows the flow pattern map of Kattan et al. plotting the flow pattern data on the mass velocity

(a) R134a

(b) R123

Fig. 5 Comparison between the observed flow patterns and Hashizume map

(a) R134a

(b) R123

Fig. 6 Comparison between the observed flow patterns and Weismamm map

versus quality coordinates. A significant feature of the map is easy to distinguish the transition qualities from one flow pattern to another. According to the experimental results of Kattan et al., the transition from stratified-wavy to annular flow was observed from the mass velocity of $G=150 \text{ kg/m}^2\text{s}$. In the VDI flow pattern map, however, the transition was observed at less value of $G=100 \text{ kg/m}^2\text{s}$ than $G=150 \text{ kg/m}^2\text{s}$. In Kattan et al. map, the transition quality from intermittent to annular flow is found to constant with approximately 0.37 at $G>150 \text{ kg/m}^2\text{s}$. 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.

4.1 Transition criterion from stratified to unstratified flow

In considering flow boiling heat transfer in horizontal tubes, it is very important to know that the annular flow is prevailing or not at any axial location of the heated tube. Thus, the observed flow patterns are classified simply into the stratified flow (including intermittent, stratified and wavy flow) and the unstratified flow (annular flow). Shah⁽¹²⁾ used the

(a) R134a

(b) R123

(c) Mixture ($X_1=0.49$)

Fig. 7 Comparison between the observed flow patterns and Kattan et al. map

liquid Froude number as the transition criterion between the all-wet and the partial-wet tube wall conditions during horizontal flow boiling. The liquid Froude number is given as

$$Fr_L = \frac{G^2}{\rho^2 g D} \quad (1)$$

When $Fr_L < 0.04$ at low mass velocity, Shah considered the tube wall as partially wetted. Kandlikar⁽¹³⁾ obtained also the same value of 0.04 for the partial-

(a) R134a

(a) R134a

(b) Mixture

(b) Mixture

Fig. 8 Comparison between the two liquid Froude number criteria and the experimental data with respect to mass flux

Fig. 9 Comparison of the experimental data for R134a and mixture against the modified liquid Froude number

wet criterion from a large amount of experimental data bank. Wattelet et al.⁽¹⁴⁾, however, recommended a much higher value of $Fr_L < 0.25$.

Figure 8 show the comparison between the two different liquid Froude numbers and the experimental data with mass velocity during horizontal flow boiling. As shown in the figure, it is found that the accuracy for predicting the transition from stratified-wavy to annular flow decreases very much as mass velocity is increased. As suggested by Kattan et al.⁽⁸⁾, these different liquid Froude number criteria were shown to be inadequate for predicting the transition from stratified to unstratified flow. It is necessary to exactly predict the transition criterion from stratified to unstratified flow because the transition criterion in flow pattern is strongly related to the heat transfer as well as pressure drop. Accordingly, in order to establish the transition criterion based on the results observed in this study during flow boiling, the liquid Froude number is corrected, and can be expressed as

$$C_{FrL} = 0.25 + \frac{G^2}{\rho^2 g D} (1-x) \quad (2)$$

From the analysis of the present flow pattern data for

both pure fluids and their mixtures, it was found that the stratified flow occurs if $C_{FrL} > Fr_L$, and the unstratified annular flow prevails if $C_{FrL} < Fr_L$. This criterion gives the condition for existence of annular flow as

$$Fr_L \geq \frac{0.25}{x} \quad (3)$$

Figure 9 indicates the comparison between the experimental data for R134a and mixture ($X_1 = 0.49$) and the liquid Froude number which is varying as a function of vapor quality proposed in this study. As shown in the figure, it is found that the transition criterion from stratified to annular flow is well predicted by Eq.(3). This becomes clear from the flow pattern map of Kattan et al. shown in Fig. 7, which are plotted on the mass velocity versus quality.

5. Conclusions

Based on visual observations, the flow pattern data were obtained with pure R134a and R123 and their mixture. The data were compared to available flow pattern maps. The conclusions are summarized as follows.

1. It was found from visual observations that for flow pattern of $G=150 \text{ kg/m}^2\text{s}$, the annular flow was hardly observed in quality less than 0.6. For $G=150$ and $600 \text{ kg/m}^2\text{s}$, the transition quality from the stratified-wavy to annular flow occurred approximately at the quality of 0.4 and 0.15, respectively.

2. The flow pattern map of Hashizume predicted well the observed flow patterns in the entire region of the intermittent, stratified-wavy and annular flow. The Weisman flow pattern map satisfactorily predicted the present data. It, however, failed to predict the flow patterns except for the annular flow. The flow pattern map of Kattan et al. predicted well the present data for each mass velocity. The transition to annular flow at high mass velocity was not predicted well from their map.

3. To predict the transition from the stratified to annular flow, the conventional liquid Froude number was modified as a function of the vapor quality. The transition criterion determined using a newly modified liquid Froude number was found to give satisfactory result in predicting the transition.

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