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New adiabatic and condensation two-phase flow pattern maps of R14 in a horizontal tube

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ABSTRACT

Heat transfer and pressure drop for two-phase flow are closely related to corresponding flow patterns. In this work, an experimental investigation on adiabatic and condensation two-phase flow patterns and their transitions of tetrafluoromethane (R14) in a horizontal tube with inner diameter of 4 mm was conducted. Experiments were implemented at mass fluxes from 200 to 650 kg/(m^2 s), saturation pressures from 1 to 3 MPa and heat fluxes from 8.2 to 28.2 kW/m^2. The observed adiabatic flow patterns were compared with six well-known flow pattern maps, none of them can predict all the transition lines accurately. Therefore, a new dimensionless number S_1, which takes account of inertia force, gravity force, shear force and surface tension force, was proposed to develop the new adiabatic flow pattern transition criteria. Eight groups of data were compared with the new adiabatic flow pattern map, most of the flow pattern data can be accurately predicted. What's more, in order to explain the effect of heat flux on condensation flow pattern transitions, another new dimensionless number S_2 was proposed by combining the dimensionless number S_1 and boiling number together. Finally, a condensation flow pattern map was proposed based on the dimensionless number S_2.

1. Introduction

With the rapid development of life science and the increasing demand of clean energy, refrigeration technology in the temperature range from 80 to 230 K is widely required. Mixed-refrigerant Joule-Thomson refrigerators (MJTR) have distinct advantages in this temperature range, as summarized by Lim et al. [1] and Gong et al. [2,3]. The working fluids of MJTR are zeotropic mixtures, which generally consist of four to seven components [4]. Tetrafluoromethane (R14) is an essential component of mixed-refrigerants. The isothermal throttle effect can be distinctly enhanced through adding R14 to the mixtures [5,6]. In addition, as a non-flammable refrigerant, R14 can also reduce the flammability of the mixtures. Accurate knowledge of the heat transfer and pressure drop of R14 is crucial for appropriate design the heat exchanger of MJTR. Moreover, the physical mechanism of two-phase heat transfer and pressure drop is closely related to flow pattern. Several heat transfer and pressure drop correlations were proposed based on flow patterns [7–13]. Therefore, the investigation and prediction of two-phase flow patterns are necessary. Over the past few decades, a large number of researchers have focused on two-phase flow.

1.1. Experimental studies on flow patterns

Several well-defined adiabatic and diabatic two-phase flow patterns have been identified. The common flow patterns in horizontal tubes are the following, bubble flow, stratified flow, wavy-stratified flow, slug flow, plug flow, annular flow and mist flow. In addition, Kim et al. [9] subdivided the annular flow into wavy-annular flow and smooth-annular flow, and the flow pattern of the transition from the slug flow to the annular flow was defined as transition flow. The classification of condensation flow patterns is similar to adiabatic flow.

An experimental study of adiabatic two-phase flow of air-water in a horizontal tube with inner diameter from 1.3 to 5.5 mm was carried out by Coleman and Garimella [14]. The results indicated that surface tension has an increasing influence on flow pattern transitions with the decreasing diameter. Resulting in the transition from intermittent flow to annular flow occurs at progressively higher vapor qualities. The same trends were also found by Weisman et al. [15] and Yang et al. [16]. Two-phase flow regimes in round (D_h = 4.91 mm), square (D_h = 4 mm) and rectangular (1.0 < D_h < 4.8 mm) horizontal tubes during condensation of

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Nomenclature

Bd	Bond number
Bo	boiling number
Ca_l	liquid Capillary number
c_p	specific heat capacity
d	distance of the temperature measurement point for copper strip
D	inner diameter
Fr_v	vapor Froude number
g	gravitational acceleration
G	mass flux
H_{lv}	latent heat
J_v	dimensionless vapor velocity
m	mass flow rate
p	pressure
q	heat flux
Q	heat power or heat quantity
Re	Reynolds number
S_1	a new dimensionless number for adiabatic flow, defined by Eq. (30)
zS_2	a new dimensionless number for condensation flow, defined by Eq. (36)
Su_v	vapor Suratman number
T	temperature
ΔT	temperature difference
We	Weber number
We^*	modified Weber number
x	vapor quality
X_{tt}	Lockhart-Martinelli parameter

Greek letters

ε	void fraction
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
η	the percentage of flow regime data that can be accurately predicted
σ	surface tension

Subscripts

A	annular flow
c	copper
i	number of the temperature measurement point
I	intermittent flow
in	inlet
j	the order of the copper strip
l	liquid phase
out	outlet
pre	preheater
S	slug flow
sat	saturation state
ST	stratified flow
sub	subcooled state
v	vapor phase
WS	wavy-stratified flow

R134a were observed by Coleman et al. [17]. It was found that hydraulic diameter has a very strong influence on the extent of each flow patterns, but the flow regime transitions are not strongly dependent on tube shape or aspect ratio. Revellin and Thome [18] fulfilled an experimental investigation in 0.5 mm and 0.8 mm diameter glass channels using R134a and R245fa. They observed that flow patterns in 0.8 mm diameter did not show any significant difference to that of 0.5 mm channel, and the transitions between different flow patterns are less influenced by the mass flux for R245fa than R134a. Ong and Thome [19] utilized R134a, R236fa and R245fa to examine the flow patterns during flow boiling in small channels of 1.03, 2.2 and 4.04 mm diameters. With the increasing mass flux, the intermittent flow is gradually suppressed and annular flow gradually spans over a wider range of vapor qualities. Barbieri et al. [20] performed experiments to observe two-phase flow characteristics of R134a in horizontal tube with inner diameter from 6.2 mm to 12.6 mm. They noted the transition qualities diminish with mass flux and increase with tube diameter, which are consistent with the trends of Ong and Thome [19]. More recently, an optical measurement method was employed by Charnay et al. [21] to visualize boiling two-phase flow patterns of R245fa along a horizontal smooth tube with hydraulic diameter of 3 mm. Intermittent flow and annular flow were observed in their study, dryout flow and mist flow did not appear. In addition, it should be emphasized that the transition between intermittent flow and annular flow is related to heat flux. Dryout flow and mist flow of R245fa were observed in the same experimental facility by Charnay et al. [22]. The influence of saturation pressure was analyzed. The macroscale (gravity being predominant over surface tension) effect increasingly becomes stronger with the increasing saturation pressure. Subsequently, the liquid film thickness at the bottom gets thicker. Park et al. [10] explored condensation flow patterns of FC72 along parallel, square channel with hydraulic diameter of 7.12 mm. Annular flow occurs in a wide range of vapor qualities with the increasing mass flux. An experimental investigation of condensation flow patterns of R290 in horizontal tubes with inner diameters of 7 and 15 mm was carried out by Milkie et al. [23]. It was obtained that the transition from annular flow to wavy flow occurs at a higher vapor quality in the 15 mm diameter tube than 7 mm. Additionally, with the increasing mass flux and saturation pressure, the transition from annular flow to wavy flow is delayed to lower vapor qualities. Zhuang et al. [24] conducted an experimental study on two-phase flow characteristics for R170 in a horizontal tube with the diameter of 4 mm. The results indicated that vapor qualities corresponding to the flow regime transitions tend to decrease with the increasing mass flux, and saturation pressure has little influence on transitions. Vanderputten et al. [25] measured two-phase condensation flow patterns of R134a at low mass fluxes in rectangular tube with hydraulic diameter of 0.84 mm. Smooth-annular and wavy-annular flow were observed, with no distinct intermittent flow. Jiang et al. [26] experimentally observed two-phase flow patterns for condensation of ethanol-water mixtures in triangular microchannels. The vapor qualities for the transition to injection flow decrease with the increasing mass flux and decreasing inlet ethanol concentration.

1.2. Flow pattern maps

Flow pattern maps are employed to predict the local flow patterns in a tube. In the past few decades, several research efforts, both analytical and experimental, were directly towards the study of two-phase flow pattern maps. One of the earliest flow pattern maps for horizontal tubes was proposed by Baker [27]. The map defined transitions between different flow regimes with property corrected vapor and liquid mass flux as the coordinate axes. Subsequently, using liquid and vapor superficial velocities as the