International Journal of Heat and Mass Transfer 55 (2012) 1754–1763

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Flow pattern maps and transition criteria for flow boiling of binary mixtures in a diverging microchannel

B.R. Fu [a], P.H. Lin [a], M.S. Tsou [a], Chin Pan [a,b,c,*]

[a] Department of Engineering and System Science, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC
[b] Institute of Nuclear Engineering and Science, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC
[c] Low Carbon Energy Research Center, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC

ARTICLE INFO

Article history:
Received 6 October 2011
Received in revised form 11 October 2011
Accepted 11 October 2011
Available online 7 December 2011

Keywords:
Flow boiling
Binary mixtures
Flow pattern map
Transition criteria

ABSTRACT

This paper presents a visualization study of flow boiling of binary mixtures (methanol–water and ethanol–water mixtures) in a diverging microchannel. The flow pattern and transition criteria are studied in terms of effects of mass flux, heat flux, and molar fraction of the more volatile component (i.e., methanol or ethanol). Four boiling regimes are identified: bubbly-elongated slug flow, annular flow, liquid film breakup, and dryout. Further, generalized flow pattern maps are constructed using coordinates of nondimensional parameter space (boiling number, Weber number, and Marangoni number), wherein relatively distinct boundaries between the flow patterns are identified. Criteria for transitions between flow patterns are proposed in the form of nondimensional groups and are successfully used to predict the experimental results. More than 92% of the data are correctly located within transition boundaries. The criterion for the onset of nucleate boiling—the boundary between single-phase flow and bubbly-elongated slug flow—is also determined for both methanol–water and ethanol–water mixtures on the basis of the same set of nondimensional parameters.

1. Introduction

The two-phase flow and boiling heat transfer of multicomponent mixtures are of fundamental importance in many areas such as chemical engineering, process industries, and refrigeration systems. In the literature, there have been numerous reports of the study of heat transfer characteristics and visualized flow patterns of the flow boiling of mixtures, especially mixed refrigerants, in small and miniature channels. For example, Wei et al. [1,2] conducted an experimental study on the two-phase flow pattern and heat transfer of a refrigerant-oil (R22-oil) mixture that underwent flow boiling in small tubes with inner diameters of 6.34 and 2.50 mm. Four boiling regimes were observed in the 6.34-mm tube: wavy, wavy annular, annular, and mist-annular flows. However, only slug-annular and annular flows were observed in the 2.50-mm tube because of the reduction in tube size. A flow pattern map was then constructed using the coordinates of superficial vapor and liquid velocities. A correlation between the two-phase heat transfer multiplier and the local properties of refrigerant-oil mixtures was also proposed. Lim and Park [3] conducted a flow visualization study on the flow boiling of R134a, R123, and their mixtures with a given concentration in a tube having an inner diameter of 10 mm. The two-phase flow patterns observed in their study consisted of intermittent (including plug and slug), stratified, stratified wavy, wavy, annular, and mist flows. They also constructed flow pattern maps for pure and mixed refrigerants. Furthermore, they proposed a criterion for the transition from stratified to annular flow on the basis of the modified liquid Froude number (as a function of the vapor quality).

Greco [4] investigated the convective boiling of refrigerants, both pure (R22 or R134a) and mixed (R404A, R410A, R507, R407C, and R417A), in a smooth, horizontal, stainless steel tube with an inner diameter of 6 mm. He determined the effects of vapor quality, evaporation pressure, heat flux, mass flux, and fluid thermophysical properties on the flow boiling characteristics and found that the heat transfer coefficients of R134a exceeded those of the other working fluids. However, flow visualization was not presented, because of the opacity of the test section. Raja et al. [5,6] conducted an experimental study on the flow boiling heat transfer coefficients and two-phase flow patterns of R134a/R290/R600a mixtures in tubes with inner diameters of 9.52 and 12.7 mm. They demonstrated that in stratified and stratified-wavy flows the heat transfer coefficients are dependent on the heat flux, indicating the prevalence of nucleation. The heat transfer coefficient for the 9.52-mm tube was higher than that for the 12.7-mm tube because of the difference in their flow patterns. The main flow patterns observed in the 9.52-mm tube were stratified-wavy and annular flows, whereas that in the 12.7-mm tube was stratified flow.

* Corresponding author at: Department of Engineering and System Science and Institute of Nuclear Science and Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC. Tel.: +886 3 571 5131x34320; fax: +886 3 572 0724.
E-mail address: cpan@ess.nthu.edu.tw (C. Pan).

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doi:10.1016/j.ijheatmasstransfer.2011.11.030

Nomenclature

Bo	boiling number (–)
C_1,C_2	constants in the corresponding equation (–)
D_h	mean hydraulic diameter (m)
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
h_{lv}	latent heat of vaporization (kJ/kg)
L_0	initial bubble length (m)
L_t	bubble length at a given time (m)
Ma	Marangoni number (–)
$Ma_{\max}$	maximum Marangoni number of the binary mixture under consideration (–)
Pr	Prandtl number (–)
q''	heat flux (kW/m^2)
q''_{CHF}	critical heat flux (kW/m^2)
T_{sat}	saturation temperature (°C)
T_w	wall temperature (°C)
t	time (s)
υ_l	liquid kinematic viscosity (m^2/s)
We_D	Weber number based on the hydraulic diameter (–)
x_m	molar fraction of the more volatile component in the liquid phase (–)
Greek symbols	
β	divergence angle of a channel (degrees)
ρ_l	liquid density (kg/m^2)
ρ_v	vapor density (kg/m^3)
σ	surface tension (N/m)
$\Delta\sigma$	difference in surface tension between fluid at the dew point and bubble point (N/m)
ΔT_{sat}	wall superheat (°C)

Hu et al. [7] experimentally studied the heat transfer characteristics of flow boiling of R410A-oil mixtures and R22-oil mixtures in a horizontal *C*-shaped tube with an outer diameter of 7 mm and curvature ratio of 60. They reported that the heat transfer coefficient for the *C*-shaped tube was smaller than that for a straight tube. Annular flow was not observed in their study, which may be the reason for the reduction in the heat transfer coefficient. Orian et al. [8] conducted an experimental study on the flow boiling of a binary solution (R22-dimethylacetamide) in a horizontal tube with a diameter of 19.05 mm. The working fluids employed in their study were different from those discussed in the literature, and temperature glide occurred above 200 °C. The boiling points of R22 and dimethylacetamide are −40.8 °C and 165 °C, respectively. Because the operating temperature was less than 100 °C, dimethylacetamide did not reach its boiling point, but R22 did. Thus, the boiling process was as attributed to the release of R22 from the liquid phase (i.e., the vapor phase was assumed to contain only R22). In the same study, Orian et al. also determined the influence of heat input, flow rate, solution concentration, and pressure on the two-phase flow pattern and heat transfer coefficient. They reported five boiling regimes in their study: bubbly, plug, stratified, stratified-wavy, and wavy flows. On the basis of their experimental observations, they constructed flow pattern maps in the plane of mass flow rate versus heat input (also heat flux).

Zou et al. [9] investigated the flow boiling heat transfer and two-phase flow patterns of R170/R290 mixtures in a horizontal tube having an inner diameter of 8 mm. They reported that the heat transfer coefficients of pure R170 and R290 are higher than those of the binary mixtures. Some two-phase flow patterns were observed in their study, such as wavy, semi-annular, and annular flows. Furthermore, flow pattern maps for pure R290 and R170/R290 mixtures were constructed using coordinates of mass flux and vapor quality. They also reported that for R170/R290 mixtures, the transition from wavy to annular flow occurred at a higher mass flux and vapor quality than for pure R290, which resulted in degradation of the heat transfer coefficient of the binary mixtures. Taboas et al. [10] conducted experimental studies on the flow boiling heat transfer and pressure drop of ammonia–water mixtures in a vertical plate heat exchanger. They showed that the boiling heat transfer coefficient is highly dependent on the mass flux, whereas the heat flux and system pressure have insignificant effects at high vapor qualities. The pressure drop increases with increasing mass flux and vapor quality, but the heat flux and system pressure have negligible effects.

Bandarra Filho et al. [11] conducted a comprehensive review of flow boiling characteristics and flow pattern visualization for refrigerant-oil mixtures. Their study indicated that a flow pattern map for the flow boiling of refrigerant-oil mixtures had not been proposed in the literature. Therefore, they suggested some important directions for future research related to the flow boiling of refrigerant-oil mixtures, such as flow pattern maps, transition criteria, and experiments in mini- and microchannels.

In 2006, Cheng and Mewes [12] had also pointed out this insufficiency: "In fact, as one important aspect of two-phase flow and flow boiling, there is no study of flow patterns and flow visualization of mixtures in the literature." Indeed, there are limited studies on the flow boiling and evaporation of binary mixtures in microchannels [13–16] and particularly few on the flow visualization and critical heat flux (CHF) of organic solutions [15,16]. This may be owing to the complexity and difficulty of such experiments. For example, Peng et al. [13] investigated the subcooled flow boiling heat transfer characteristics of methanol–water mixtures in microchannel plates. They found that the liquid compositions of the more volatile component (i.e., methanol) had a significant effect on the boiling heat transfer characteristics. They also found that the flow boiling heat transfer was enhanced at low concentrations ($\leqslant$36.0%) but reduced at high concentrations ($\geqslant$51.1%). Sun and Shi [14] explored the flow boiling of methanol–water mixtures in rectangular microchannels with or without artificial cavities (diameter of 12 μm) under the condition of a controlled but increasing heat flux. They also demonstrated that boiling heat transfer is strongly influenced by the liquid composition. Nevertheless, flow visualizations were not explicitly presented in Refs. [13,14].

Many flow pattern maps for the flow boiling of a pure component in a microchannel are available in the literature (mostly for refrigerants or water). For example, Revellin and Thome [17] proposed a flow pattern map for the flow boiling of R134a and R245fa, which was constructed using coordinates of superficial vapor and liquid velocities as well as mass flux and vapor quality. Three flow boiling regimes were identified in their study: isolated bubble, coalescing bubble, and annular regimes. Harirchian and Garimella [18] presented a flow regime map for the microchannel flow boiling of FC77. Quantitative transition criteria based on nondimensional parameters (including boiling number, Bond number, and Reynolds number) were proposed accordingly. Singh et al. [19] proposed a flow pattern map for the flow boiling of water in a silicon microchannel. They observed bubbly, slug, and annular flow regimes in their study. Using experimental observations, they constructed flow pattern maps in planes of heat flux versus vapor quality and volumetric flow rate versus vapor quality. Wang et al. [20] conducted a study on two-phase flow patterns of water in a narrow channel. Four flow patterns were reported: dispersed bubbly, coalesced bubbly, churn, and annular flows. In their study,