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Flow-pattern-based correlations for pressure drop during flow boiling of ethanol–water mixtures in a microchannel

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ABSTRACT

This paper constitutes an experimental investigation into the pressure drop during flow boiling of ethanol–water mixtures in a diverging microchannel with artificial cavities. Similar to boiling curves, the experimental results reveal that the single-phase and boiling two-phase flow pressure drops are significantly influenced by the molar fraction. The single-phase pressure drop for water demonstrates the smallest as the water viscosity is smaller than that of ethanol–water mixtures. During flow boiling, in general, two-phase flow pressure drop at a given wall superheat for the mixture with molar fraction of 0.1 is the highest, due to the higher boiling heat flux resulted from the Marangoni effect. Based on the correlation development of boiling heat transfer coefficient in the previous study, two flow-pattern-based empirical correlations for the two-phase frictional pressure drop are proposed in the terms of non-dimensional parameters, such as boiling number, Weber number, and Marangoni number. The proposed correlations are similar to the empirical correlation for boiling heat transfer coefficient with different numerical values of the coefficients and exponents. Different values of flow-pattern-based constant are obtained for different flow patterns. The constants for annular flow and liquid film breakup are the same. It may be due to the major mechanism of the two-phase flow is liquid film evaporation for these two flow types. The overall mean absolute errors of the proposed correlations are 13.7% and 11.6%, respectively. More than 90% of the experimental data can be predicted within a ±25% error band. Such an excellent agreement confirms that the proposed correlations may predict the Marangoni effect on the two-phase flow pressure drop during flow boiling of binary mixtures in a microchannel.

1. Introduction

Boiling of multi-component mixture is of importance and interest for many applications such as in chemical engineering, in process industries, and for refrigeration systems. Studies on pool boiling of mixtures are widely available in the literature. For example, some up-to-date studies on pool boiling of mixtures are reported by Inoue and Monde [1], Sathyabhama and Ashok Babu [2], Peyghambarzadeh et al. [3], and Sarafraz and his co-workers [4–7]. In addition, there are also many studies on flow boiling of mixtures, mostly mixed refrigerants, in small channels [8–17]. However, there are few researches on flow boiling of mixtures in a microchannel. The flow boiling characteristics of multi-component mixture in a microchannel are more complicated than that of pure component. The concentration of mixtures is expected as one of the most important factors during boiling process.

In Lin et al. [18], the convective boiling heat transfer and critical heat flux (CHF) of methanol–water mixtures in a diverging microchannel with artificial cavities was investigated. They found that at the same mass flux, the CHF increases slightly as the molar fraction (x_m) ranges from 0 (pure water) to 0.3 (methanol–water mixtures) and then decreases as the molar fraction ranges from 0.3 to 1 (pure methanol). The maximum CHF is reached at a molar fraction of 0.3, especially for the highest mass flux (G) of 175 kg/m^2 s, owing to the Marangoni effect. A mechanism of Marangoni effect is due to differences in surface tension and may induce an additional liquid restoring force to the three-phase contact line [19]. The flow pattern of liquid film breakup at the molar fraction of 0.3 persists up to a higher heat flux than that at other molar fractions. The Marangoni effect drives the liquid flow toward the contact line, resulting in a higher heat flux and a higher critical heat flux. An empirical CHF correlation, involving the Marangoni number, for flow boiling of binary mixtures has been proposed as follows [18]:

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Nomenclature

A_h	total heated area of the channel (m^2)
Bo	boiling number (–)
C_c	contraction coefficient (–)
C_i	flow-pattern-based constant in the corresponding equation, $i = 0,1,2,3$ (–)
D_h	mean hydraulic diameter (m)
f	friction factor (–)
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (kW/m^2 K)
h_{lv}	latent heat of vaporization (kJ/kg)
L	channel length (m)
Ma	Marangoni number (–)
m	total mass flow rate (kg/s)
Pr	Prandtl number (–)
q''	heat flux (kW/m^2)
Re	Reynolds number (–)
T	temperature (K)
υ_l	liquid kinematic viscosity (m^2/s)
W	channel width (m)
We_D	Weber number based on the hydraulic diameter (–)
X^2	Lockhart–Martinelli parameter (–)
x	quality (–)
x_m	molar fraction of the more volatile component in the liquid phase (–)

Greek symbols

α	void fraction (–)
β	divergence angle of a channel (°)
γ	contraction or expansion area ratio (–)
λ	aspect ratio (–)
ρ	density (kg/m^3)
σ	surface tension (N/m)
$\Delta h_{sub,\ in}$	enthalpy change corresponding to the inlet subcooling (kJ/kg)
$\Delta\sigma$	difference in surface tension between fluid at the dew point and bubble point (N/m)
ΔP	pressure drop (kPa)
ΔT_{sat}	wall superheat (K)

Subscripts

a	acceleration
CHF	critical heat flux
f	frictional
h	homogeneous
in	channel inlet
l	liquid
max	maximum
out	channel out
sat	saturation
sp	single-phase
tot	total
tp	two-phase
v	vapor
w	wall

$$q''_{CHF} = 0.00216 G h_{lv} We_D^{-0.078} \left(1 - 0.44 \frac{Ma}{|Ma_{max}|}\right)^{-1} \quad (1)$$

where h_{lv} is the latent heat of the vaporization, $We_D = (G^2 D_h)/(\sigma \rho_l)$ is the Weber number based on the hydraulic diameter of the channel (D_h), and Ma is the Marangoni number, defined by Fujita and Bai [19] as:

$$Ma = \frac{\Delta\sigma}{\rho_l \upsilon_l^2} \left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} \cdot Pr \quad (2)$$

here $\Delta\sigma$ is the difference in the fluid surface tension between the dew point and the bubble point, σ is the surface tension of the fluid, ρ_l is the liquid density, ρ_v is the vapor density, υ_l is the liquid kinematic viscosity, g is the gravitational acceleration, and Pr is the Prandtl number.

Recently, Fu et al. [20], a follow up study of Lin et al. [18], reported the visualization of flow boiling of binary mixtures (methanol–water and ethanol–water mixtures) in a microchannel. Four boiling regimes were reported: bubbly-elongated slug flow, annular flow, liquid film breakup, and dryout. The flow visualization results demonstrated that liquid film breakup persists up to the highest heat flux at molar fractions of 0.3 and 0.1 for the methanol–water and ethanol–water mixtures, respectively. This is because the Marangoni effect is most significant at these particular molar fractions. They also constructed flow pattern maps in the plane of heat flux versus molar fraction of methanol or ethanol. A significant effect of the molar fraction on the evolution of the two-phase flow pattern is observed, especially in the liquid film breakup regime. In addition, 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. Consequently, they further proposed transition criteria between flow patterns in the form of nondimensional groups as follows:

$$Bo \cdot \left(1 - 0.44 \frac{Ma}{|Ma_{max}|}\right) = C_1 We_D^{C_2} \quad (3)$$

where C_1 and C_2 are flow-pattern-based constants, and $Bo = q''/(G h_{lv})$ is the boiling number. The boundary between liquid film breakup and dryout is consistent with the correlation for the CHF of binary mixtures, i.e., Eq. (1).

Fu et al. [21], further complementary to studies of Lin et al. [18] and Fu et al. [20], investigated experimentally the convective boiling heat transfer and the critical heat flux of ethanol–water mixtures in a diverging microchannel. The CHF data in their study show an excellent agreement and demonstrate a consistent trend with an empirical correlation for the CHF prediction, i.e., Eq. (1), proposed by Lin et al. [18]. They also reported that the two-phase heat transfer coefficient is much higher than that of single-phase convection region and is significantly affected by the wall superheat and the molar fraction. The two-phase heat transfer coefficient reaches a maximum in the region of the bubbly-elongated slug flow and deceases with a further increase in the wall superheat until approaching a condition of CHF, indicating that the heat transfer is mainly dominated by convective boiling. Furthermore, they proposed a flow-pattern-based empirical correlation for the two-phase heat transfer coefficient (h_{tp}) of flow boiling of ethanol–water mixtures as follows:

$$h_{tp} = C_3 Bo^{-0.27} We_D^{-0.67} \left(1 - 0.44 \frac{Ma}{|Ma_{max}|}\right)^{-0.84} \cdot h_{sp} \quad (4)$$

where C_3 is a flow-pattern-based constant and h_{sp} is the single-phase heat transfer coefficient.