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Experimental and analytical study on nucleate pool boiling heat transfer of R134a/R245fa zeotropic mixtures

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ABSTRACT

In the present study, the nucleate pool boiling heat transfer characteristics of zeotropic binary mixtures (R134a/R245fa) with different blending ratios, as well as their pure components, were experimentally investigated in a visualized pressure vessel. For each test refrigerant, the experiments were performed on a horizontal plain copper surface (10 mm × 10 mm) at the same evaporating temperature of 26 °C with the heat flux ranging from 1.2 kW/m^2 to 360 kW/m^2. The boiling curves of test refrigerants were subdivided into up to four zones from natural convection region to bubble column region according to the visualization results. The slope of the boiling curve in bubble coalescence region was greater than that in isolated bubble region. The onset of nucleate boiling (ONB) point of zeotropic mixtures obviously lagged behind that of pure components, namely, the higher wall superheat was required, which presented the consistent variation with the temperature glide. The boiling heat transfer coefficient of zeotropic mixtures, although increasing with the increase of heat flux, was degraded compared to the corresponding ideal heat transfer coefficient, except for some specific cases with high heat flux. Based on the analysis of heat transfer degradation factors and additional mass transfer resistance, the nucleate pool boiling process of zeotropic mixtures was identified as three stages due to the presence of two inflection points, pseudo fully developed nucleate boiling (P-FDNB) point and pseudo double boiling (P-DB) point. The wall superheat of test mixtures at P-DB point was stable at a certain value and did not vary with the blending ratio. The thermodynamic fluctuation theory was introduced to describe the effect of mass transfer resistance for zeotropic mixtures at P-DB point and the calculation results showed good agreement with the experimental data.

1. Introduction

In the past few years, more attention has been focused on the research of refrigerants to extend their use as working fluids from refrigeration or air-conditioning systems to new application areas. Boiling heat transfer of refrigerants is not only widely used in conventional engineering and industrial fields, but also can be adopted as a highly efficient means of thermal management to dissipate high heat flux from critical devices to maintain a reasonable operating temperature range, making up for the inadequacy of air cooling method and single phase liquid cooling technology [1,2]. As the major substitutes of ozone depletion refrigerants (CFCs and HCFCs), zeotropic mixtures of HFCs have been proven to be effective in improving the cooling capacity and energy efficiency of refrigeration cycle as well as reducing the GWP of pure HFCs [3]. It is also promising for zeotropic refrigerant mixtures to improve the operating performance of organic Rankine cycle (ORC) since the characteristic of temperature glide during phase change at constant pressure can be an advantage to reduce the heat transfer irreversibility in heat exchanger [4]. More importantly, zeotropic mixtures show great potential in the urgent need to address the cooling demands for high power and high heat flux electronic devices, because the recent studies indicate that the zeotropic mixtures can obviously delay or even avoid drying out and increase the critical heat flux (CHF) [5,6]. Therefore, it is of great significance to investigate the nucleate pool boiling heat transfer of zeotropic mixtures for the sake of system optimization and cooling technology development.

Numerous experimental and theoretical studies have been carried out about the nucleate pool boiling characteristics of pure refrigerants, including heat transfer performance, bubble behavior,

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Nomenclature

A_b	area of boiling surface (m^2)
D	degradation factor
F	factor of concentration fluctuation
H	distance from the thermocouple holes to the boiling surface (m)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/m K)
L	side length of the boiling surface (m)
M	molar mass (g/mol)
n	mole number
P	probability distribution law for the fluctuation
Q	heating power (W)
q	heat flux (W/m^2)
S	entropy (J/K)
T	temperature (K)
ΔT_{db}	temperature glide (K)
U	voltage (V)
ΔY	mass fraction difference
Greek symbols	
ρ	density (kg/m^3)
φ	mass fraction of volatile component
ϕ	molar fraction
Subscripts	
b	nucleate boiling
eva	evaporation
id	ideal
sup	superheat
l	liquid (Part I)
v	vapor (Part II)
w	wall
1	volatile component
2	less volatile component

nucleation mechanism and relevant prediction method, etc. [7–10]. Besides, many researchers have experimentally investigated the boiling phenomena of zeotropic mixtures through the method of adding volatile component into water. For example, Stralen and Sluyter [11,12] explored the pool boiling of 1-butanol/water and 2-butanone/water and found that the CHFs for binary mixtures were able to be increased or decreased depending on the blending ratios. The research conducted by Mcgillis and Carey [13] illustrated that the additional liquid restoring force induced by the differences in surface tension, known as the Marangoni effect, strongly affected the pool boiling of 2-propanol/water and methanol/water. Fujita and Bai [14] proposed the correlation for binary mixtures in pool boiling by introducing the Marangoni number for various types of mixtures, such as methanol/water, ethanol/water, ethylene glycol/water and so on. Armijo and Carey [15] also employed an average pseudo single-component coefficient to improve the prediction accuracy for the strong Marangoni effects of mixtures due to the large surface tension variation with concentration. Hamzekhani et al. [16] developed a prediction method of vapor bubble departure diameter utilizing Buckingham theory based on the extensive new experimental data of pool boiling for ethanol/water mixtures. All of these studies provided the basic understanding and meanwhile laid the research foundation for the nucleate pool boiling of refrigerant mixtures.

At present, a number of papers have been published with respect to the pool boiling experiments of zeotropic refrigerant mixtures. Based on the measured pool boiling heat transfer coefficients of R12/R113 and R22/R11 at pressure ranging from 0.25 to 0.7 MPa and heat flux ranging up to critical heat flux, Inoue et al. [17] found that the boiling heat transfer performance of zeotropic binary mixtures were deteriorated, and they established an evaluation model treating the raising bubble point temperature due to the preferential evaporation of volatile component as the main impact factor. Chiou et al. [18] proposed a correlation with the pool boiling experimental data of R22/R124 and predicted the heat transfer deterioration with reasonable accuracy. Jung et al. [19] investigated the nucleate pool boiling heat transfer of R32, R125, R134a and their binary mixtures on a horizontal smooth tube and the reductions of heat transfer coefficients were also reported for zeotropic mixtures. With the comparison of four well known correlations, they developed a new correlation by utilizing only the phase equilibrium data and physical properties. Sun et al. [20] and Zhao et al. [21] also did some similar work to the above. Through the observation of bubble behaviors for pool boiling of R11/R113, Diao et al. [22] pointed out that the blending ratio of binary mixtures had an important effect on the nucleation site density, bubble departure diameter and frequency due to the mass transfer resistance. Recently, Gong et al. [23] conducted a comprehensive study on nucleate pool boiling of R170, R600a and their binary mixtures based on the visualization method. Both of the heat transfer coefficient and bubble departure diameter were compared with the existing correlations and the related mixture effect factors for selected correlations using the experimental data were modified. Besides, they found that the mixture effects presented non-linear influence on bubble size and departure frequency with the variation of mixture composition. Based on the visualized pool boiling experiments of R134a/R32 and R600a/R290, He et al. [24] suggested an impact factor of concentration fluctuation and proposed a correlation to predict the nucleate site density for binary mixtures.

In order to reveal the pool boiling mechanism of zeotropic mixtures, several scholars have conducted the relevant studies using analytical and numerical methods to characterized the degraded heat transfer performance. Wang and Tan [25] proposed an analytical model for pool boiling heat transfer of binary mixtures base on the concept that the boiling heat transfer coefficient was reduced by the mass transfer resistance as well as the nonlinear effect. With the theoretical analysis, a new pseudo-single component heat transfer coefficient was introduced to account for the mixture property effects by Kandlikar [26], which also be examined by refrigerant mixtures and other binary mixtures, such as ethylene/water and methanol/water. Li et al. [27] theoretically analyzed the effects of interfacial behavior on bubble dynamics and heat transfer of nucleate boiling for binary mixtures. They presented that the Marangoni effect also played an important role in the nucleate boiling process besides the mass transfer resistance. Kern and Stephan [28] described the nucleate boiling heat transfer of binary mixtures at low and intermediate heat flux based on the numerical simulation work of a single bubble model. The modeling equations were derived with the simplified conservation equation as well as the consideration of microscale and mixture effects, such as microlayer evaporation, diffusive mass transfer and Marangoni convection. Glavatskiy and Bedeaux [29] calculated the heat and