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Experimental investigation of single bubble growth in the boiling of the superheated liquid mixed refrigerants

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ABSTRACT

The reduction of the bubble growth rate in mixed liquid refrigerants is one of the main reasons for the reduction of the boiling heat transfer coefficient. To study the mass diffusion effect and the reduction of the bubble growth rate in boiling of non-azeotropic mixtures, an experiment was conducted to investigate the bubble growth rates of R142b, R134a, isobutane and R142b/R134a mixtures in a vertical transparent quartz tube. The pressure used in this experiment ranged from 0.2 to 0.47 MPa, and the superheats ranged from 1.5 to 23.3 °C. Moreover, in order to obtain a uniformly superheated liquid, the bubbles were grown at a single nucleation site, and the departure frequency for the successive bubbles was lower than 20 Hz. Experimental bubble growth constants were obtained, and the reliability of the experimental study was supported by theoretical models for pure refrigerants. Additionally, for the study of bubble growth rate in binary mixtures, the attenuation factors for superheat were calculated and compared with different proposed models. The experimental attenuation factors were much smaller than the calculated results. Thus, a correlation was identified, and the errors were primarily in the range of −30% to +30%.

1. Introduction

Boiling of mixtures is widely adopted in chemical processes [1,2]. In the past few decades, this has been studied by many researchers because the boiling heat transfer performance of mixtures were much worse than pure refrigerants. The deterioration of the heat transfer coefficient, the reduction of the nucleation site density, the mass transfer resistance and the effect of mixtures on the onset of boiling were studied experimentally and theoretically [3–9]. Moreover, the deterioration of the bubble growth rate is also one of the main reasons for the reduction of the heat transfer coefficient during boiling of the mixtures. And the effect of mass diffusion on mixture boiling is still not clear.

The bubble growth process in the boiling of pure refrigerants has been studied extensively [10]. Models for the bubble growth rate have been proposed, and the bubble growth process has been separated into inertia controlled growth and heat transfer controlled growth [11]. Researchers mainly focused their studies on the heat transfer controlled regime because the inertia controlled process is very short (several ms).

For the study of bubble growth in superheated liquid, scholars have developed analytical relationships for the bubble growth rate based on thermal diffusion. Then Plesset et al. [12] and Forster et al. [13] obtained the approximate solutions respectively. In these studies, the bubble growth rate is proportional to Jakob number, the square root of thermal diffusivity and the square root of time. Moreover, researchers have also conducted experimental studies on the bubble growth rate in superheated liquid. Florchuetz et al. [14] studied the growth rates of free vapor bubbles in liquids at uniform superheats and they obtained the superheated liquid by suddenly depressurizing the system. Ivashnyov et al. [15] developed a mathematical model for the thermal growth of a vapor bubble moving in superheated liquid, and in their study, the experimental results from Florchuetz et al. [14] were analysed.

The bubble growth process for the pure refrigerants on a heated surface is much more complicated. Theoretical and experimental research has been conducted [16–18] and the heat transfer mechanisms for growth of the bubble are: condensation at the bubble cap, heat transfer from the superheated macro region and evaporation from a microlayer beneath the bubble [19,20]. In 1969, Cooper et al. [21] proposed that the evaporative micro layer plays an important role in the boiling heat transfer process. After that, many researchers have tried to measure the temperature and the thickness of the evaporative microlayer in the growth process of

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Nomenclature

T	temperature (K)
P	pressure (MPa)
DT	temperature difference (°C)
f	bubble departure frequency (Hz)
Q	heat flux (W)
t	time (s)
Ra	micro-roughness (nm)
x	the concentration in the liquid phase at equilibrium
y	the concentration in the vapor phase at equilibrium
$\tilde{x}$	the concentration in the liquid phase around the bubble
$\tilde{y}$	the concentration in the vapor phase in the bubble
C	experimental bubble growth constant ($\mathrm{m \cdot s^{-0.5}}$)
D	diameter of the bubble (m)
L	length (m)
Ja	Jakob number
a_l	thermal diffusivity ($\mathrm{m^2 \cdot s^{-1}}$)
C_p	specific heat capacity ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)
h_{lv}	latent heat ($\mathrm{J \cdot kg^{-1}}$)
K	attenuation factor for the superheat
ΔT_{db}	temperature difference of the dew point and bubble point (°C)
M_2	molecular weight of the solvent (g/mol)
V_1	liquid volume of the solute under 0.101 MPa at the boiling point ($\mathrm{cm^3/mol}$)

Greek symbols

θ	contact angle (°)
σ	surface tension ($\mathrm{N \cdot m^{-1}}$)
β	experimental bubble growth constant
ρ	density ($\mathrm{kg \cdot m^{-3}}$)
κ_l	mass diffusivity ($\mathrm{m^2 \cdot s^{-1}}$)
ψ_2	association factor of the solvent
μ	viscosity (cP)
λ	thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)
l_t	thickness of thermal boundary layer (m)

Subscripts

w	wall
sat	saturation
$app1$	appearance of the first bubble
$app2$	appearance of the second bubble
l	liquid phase
v	vapor phase
$Tank$	water tank
$Tube$	quartz tube
Bub	bubble
Pix	pixel
Eff	effective
Exp	experimental
Mix	mixture

a bubble [22–24]. Based on these mechanisms, bubble growth models were developed. Yun et al. [25] proposed a bubble growth model that considers condensation at the bubble cap. In the models developed by Cooper et al. [21] and Van Stralen et al. [26], the effect of the evaporative micro layer was considered. Moreover, in recent years, the bubble growth rate in flow boiling condition was analysed by Colombo et al. [27] and Sumit et al. [16]. Because of these complicated mechanisms in pool boiling, during the bubble growth process, the effect of mass diffusion can't be measured accurately.

Compared to the large number of studies of the bubble growth process in pure refrigerants, similar studies are relatively rare for binary mixtures. The growth of bubbles in mixed refrigerants is further more complicated. And the mass diffusion effect have large impact on the bubble growth process. For a non-azeotropic mixture, the concentration of the more volatile component in the vapor bubble $\tilde{y}$ is higher than that in the liquid phase around the bubble $\tilde{x}$ and the concentration of the more volatile component in the bulk liquid x is lower than $\tilde{x}$. As a result, the more volatile component in the liquid layer around the bubble should diffuse through the concentration boundary layer, and the degree of superheat in the bubble interface is lower [28].

The first analytical bubble growth model for binary mixtures in the superheated liquid was developed and improved by Scriven et al. [29] and Van Stralen et al. [26]. In this model, the effect of mass diffusion and the reduction of superheat was considered. However, they could not obtain the concentration of every component at the bubble interface. From their perspective, the reduction of bubble growth rate in non-azeotropic mixtures was related to the concentration difference in the vapor and liquid phase $|x - y|$. Moreover, Van Stralen et al. [26] also developed a bubble growth model for binary mixtures on a heated wall. In this model, the effect of the relaxation layer and the evaporative microlayer were considered, and the effective superheat and a dimensionless mixture bubble growth parameter were used.

Using a high-speed camera, experimental studies have been conducted to investigate the bubble growth process in the binary mixtures. The bubble growth rate in mixtures on a heated surface was experimentally studied by Diao et al. [30] and Kim et al. [31], etc. However, the effect of mass diffusion on bubble growth in mixtures could not be thoroughly evaluated because the bubble growth rate is affected by different heat transfer mechanisms (the liquid is evaporated in the microlayer, and the vapor is condensed at the bubble cap). Moreover, Florschuetz et al. [28] have obtained the bubble growth rate for ethanol/water and water/isopropanol mixtures in superheated liquids and the bubble growth condition was simplified. In their study, a uniformly superheated liquid was obtained by a sudden reduction of pressure in the system. Thus, the nucleation site density and bubble departure frequency could not be controlled, and the growth rate of the bubbles would be affected by each other. Additionally, the concentration around the bubble interface could not be obtained until 2011. The temperature gradient and the concentration of acetone/isopropanol in the vicinity of boiling bubbles were experimentally determined by Knauer et al. [32] using one-dimensional Raman spectroscopy.

The purpose of this study is to investigate the effect of mass diffusion on bubble growth in non-azeotropic mixtures. So the effect of mass diffusion on boiling of mixed refrigerants can be better understood. A novel experimental test facility was designed and constructed. R142b, R134a, isobutane and R142b/R134a mixtures were used as test refrigerants. The bubbles were grown in a uniformly superheated liquid at a single nucleation site. The departure frequency of the successive bubbles was set to lower than 20 Hz by adjusting the degree of superheat. Moreover, the effect of the heated wall was minimized because the wettabilities of the refrigerants were good [7,33]. Thus, the bubble growth process in this study was close to homogeneous bubble growth, and the effect of mixtures on bubble growth could be evaluated precisely. Additionally, the bubble growth rate in this experimental test