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Bubble growth model in uniformly superheated binary liquid mixture

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ABSTRACT

A novel model was developed to investigate the fundamental heat transfer and mass diffusion mechanisms of bubble growth in uniformly superheated ethanol–water mixture. In the proposed model, the energy equation was applied coupling with the quadratic temperature distribution within the thermal boundary layer. The mass diffusion effect was accounted by the introduction of species conservation equation in combination with the quadratic concentration distribution within the concentration boundary layer. Peng-Robinson equation of state and activity coefficient calculation were also adopted for the estimation of vapor-liquid equilibrium. In the present study, the maximum mass diffusion limited growth rate was proposed to quantify and illustrate the effect of mass diffusion on bubble growth. The results show that the bubble growth process in a binary mixture can be divided into three distinctive stages. The later stage of bubble growth is mainly subject to mass diffusion and partly to heat transfer at low ethanol concentrations.

1. Introduction

With the rapid development of the miniaturization and integration of electronic components, spray cooling has attracted extensive attentions worldwide and received comprehensive investigations [1]. Spray cooling, as an effective high heat flux removal method, possesses several unique advantages such as small demand of working fluid, spatial uniformity of heat removal and no boiling hysteresis, etc. [2,3].

During spray cooling, a thin liquid film is formed by liquid droplets impinging on the heated surface. A large amount of heat is dissipated through the evaporation and convection of the liquid film at a relatively low surface temperature [4]. As the surface temperature continues to rise, spray cooling enters the nucleation boiling regime when numerous bubbles are generated within the liquid film or on the heated surface. Two types of bubbles are identified according to the different positions of the initial nuclei, i.e. surface nucleation bubbles which appear in the nucleation sites on the heated surface, e.g. the pit, scratch or crevice and secondary nucleation bubbles which form on the droplet surface or within the liquid film [5]. Previous studies [6,7] showed that the efficient heat transfer of spray cooling in the nucleation boiling regime is mainly due to the existence of secondary nucleation bubbles.

In the open literatures [8–12] it was found that the surfactant and soluble additive can improve fluid characteristics and heat transfer efficiency obviously. To the best of our knowledge, few theoretical research has been conducted on the heat transfer performance of spray cooling with binary mixtures, although it has been investigated extensively through experiments [8–12]. Qiao and Chandra [8] measured the surface temperature using a spray of pure water and an aqueous solution containing sodium dodecyl sulfate (SDS) with different concentrations. The results indicated that the heat transfer performance in nucleate boiling regime was significantly improved by adding a small amount of SDS. Furthermore, the initial temperature required to initiate vapor bubble nucleation was reduced with the addition of SDS. The same soluble additive was also used in the experiment carried out by Jia et al. [9] and lower superheat and larger stable critical heat flux temperature range were identified with the introduction of the additive, indicating that using the additive is a potential method to avoid burnout of heat transfer device. Cheng et al. [10] experimentally studied the effect of high-alcohol surfactant (HAS) and dissolving salt additive (DSA) on the heat transfer enhancement of water spray cooling and concluded that HAS and DSA have different heat transfer enhancement mechanisms. The experimental study was further extended by Ravikumar et al. [11,12] who focused on the effects of anionic surfactant, cationic surfactant and nonionic surfactant on transient spray cooling. The results revealed that the binary surfactant mixtures have more superior heat transfer performance than single surfactant, and the enhanced heat transfer is due to low surface tension and high wettability.

Bubble growth dynamics is the most important subphenomenon in the nucleation boiling regime of spray cooling.

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Nomenclature

A, B, C	coefficient in Antoine equation [–]
a	attractive term in PR equation [–]
b	co-volume in PR equation [–]
c_p	constant-pressure specific heat [J/(kg·K)]
c_v	constant-volume specific heat [J/(kg·K)]
D	mass diffusion coefficient [m^2/s]
E	internal energy [J]
G^E	excess of Gibbs free energy [J/kg]
G_{ij}	coefficient in NRTL equation [–]
g_{ji}-g_{ij}	coefficient in NRTL equation [–]
h_{fg}	latent heat of vaporization [J/kg]
I	the ratio introduced in Eq. (33) [–]
k	thermal conductivity [W/m·K]
k_{ij}, l_{ij}	coefficient in PR equation [–]
L	characteristic length scale [m]
M	molar mass [g/mol]
m	mass [kg]
n	amount of substance [mol]
P	pressure [Pa]
$[P]$	parachor [–]
Q	rate of heat transfer [J]
R_g	gas constant [J/(kg·K)]
R	bubble radius [m]
r	distance from bubble center [m]
T	temperature [K]
ΔT	temperature difference [K]
t	time [s]
u	velocity [m/s]
V	mole volume [m^3/mol]
x	mole fraction [–]
y	mass fraction [–]

Greek symbols

ζ	dimensionless parameter in Eq. (1) [–]
δ_t	thermal boundary layer thickness [m]
δ_m	concentration boundary layer thickness [m]
γ	activity coefficient [–]
α	thermal diffusivity [m^2/s]
α_{ij}, τ_{ij}	coefficient in NRTL equation [–]
ρ	density [kg/m^3]
σ	surface tension [N/m]
μ	kinematic viscosity [N·s/m^2]
φ	dimensionless parameter in Eq. (5) [–]
ω	acentric factor [–]
κ	coefficient in PR equation [–]
χ	coefficient in Eq. (A.7) [–]

Subscripts

0	initial
1	more volatile component
2	less volatile component
c	critical
HT	heat transfer control
i, j	species
l	liquid
MT	mass transfer control
r	radical
s	bubble surface
sat	saturation
sup	superheat
v	vapor
∞	far field

Amounts of research has been conducted since the 1920s on mono-component bubble growth in uniformly superheated liquid or on the heated surface. Detailed overviews of these bubble growth models are summarized in Refs. [13,14]. The boiling of a binary liquid mixture is different from that of pure liquid because heat transfer and mass diffusion are closely connected with each other for the former. However, there are much fewer theoretical or experimental investigations available in the literature which predict binary bubble growth characteristics than that on unary bubble growth. Furthermore, scarcely did these models quantificationally describe the effect of mass diffusion on bubble growth in a binary mixture. One of the pioneering theoretical work on spherical bubble growth in a binary mixture was conducted by Scriven [15], who derived an analytical expression with an additive term taking account of the mass diffusion. However, the inertial, viscous and surface tension effects were all neglected. Subsequently Van Stralen [16] proposed a new dimensionless group called vaporized mass diffusion fraction to deduce an asymptotic approximation of bubble growth similar to that of unary bubble growth with a tuning constant. Skinner and Bankoff [17,18] further extended Scriven's theory from initially uniformly superheated binary mixtures to arbitrary spherically symmetric initial conditions. Van Stralen's expression was also adopted in Kandlikar's pseudo-single component heat transfer model [19]. The model was used to analytically predict the liquid composition and the temperature at the interface of a growing spherical bubble and to estimate their effect on the heat transfer in pool boiling. However, a recent study [20] indicated that the Kandlikar method significantly underestimate the heat transfer coefficient because the diffusion process considered in that model produces much larger heat transfer resistance than that actually occurs.

The binary mixture boiling phenomenon, which requires a complete formulation of a combined heat transfer and mass diffusion problem, is much more complex than that of pure fluid. In general, the saturation pressure and other thermo-physical properties of a binary liquid mixture vary with the component concentration and temperature. As a result, the microscopic bubble growth exhibits some distinctive characteristics. In the current work, ethanol-water binary mixture is chosen as the working fluid since ethanol can avoid the potential nozzle clogging or device corrosion caused by soluble salt additives. Furthermore, our previous experiment [21] confirmed that the ethanol-water binary mixture can enhance heat transfer effectively. The growth of an isolated bubble is studied with a thin thermal boundary layer and concentration layer taken into consideration. The present study is the extension of the previous work by Liu et al. [22], in which a unary bubble thermodynamic model was proposed. The model calculations can help to comprehensively understand the bubble dynamics of a bi-component mixture during spray cooling process and the maximum mass diffusion limited growth rate is proposed to quantify and illustrate the effect of mass diffusion on bubble growth.

2. Mathematical model

As illustrated in Fig. 1, the growth of a vapor bubble maintained in spherical symmetry in infinite and uniformly superheated binary liquid is investigated in this study. The following assumptions are made to simplify the present model: (1) The bubble is assumed to be stationary and the convective effect is negligibly small; (2) The vapor concentration and temperature fields inside the bubble are uniform since the diffusion in the vapor phase is much more