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Bubble growth characteristics in bi-component liquid: Influence of component concentration and liquid temperature

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HIGHLIGHTS

- A new model was proposed for bubble growth in superheated binary liquid mixture.
- The fundamental heat transfer and mass diffusion mechanisms were investigated.
- The late stage of bubble growth in a mixture is mainly governed by mass diffusion.
- High liquid temperature and light component content are in favor of bubble growth.

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ABSTRACT

A thermodynamic model for bubble growth in superheated liquid mixture was developed to investigate the heat transfer and mass diffusion mechanisms. The influence of component concentration and liquid temperature on bubble growth characteristics is the main focus of the present study. In the proposed model, the energy equation and the component diffusion equation for the liquid were coupled with the assumed quadratic temperature and concentration distribution within the liquid boundary layer. The vapor-liquid equilibrium of the binary mixture was estimated by the non-random two-liquid (NRTL) equation. The comparison between the current calculated results with the available experimental data demonstrates the accuracy of the proposed bubble growth model. The results show that the later stage of bubble growth in a binary mixture is primarily controlled by mass diffusion and also influenced by heat transfer. The bubble growth characteristics strongly depend on the mass fraction of the more volatile component and the liquid temperature. Both higher liquid temperature and concentration of the light component are beneficial to enhance the bubble growth. The effect of mass diffusion on bubble growth becomes weaker with increasing liquid temperature and decreasing initial mass fraction of the more volatile component.

1. Introduction

As a fundamental process with vapor-liquid phase change, bubble growth in superheated liquid is pretty common in thermal and chemical engineering, including electrolytic process, polymeric foaming, mineral processing, ink-jet printing, spring cooling and so forth (Lesage et al., 2013). In the case of spray cooling to remove high heat flux, numerous secondary nucleation bubbles are responsible for the high-efficiency heat transfer in the nucleate boiling regime (Rini et al., 2002; Tan et al., 2013). This is associated with the fact that enormous latent heat of phase change is capable of dissipating high heat flux effectively.

Considerable efforts have been made over the past few decades to improve the heat transfer efficiency of spray cooling. A number of studies found that some additives, e.g. surfactant, soluble salt or nanoparticle, can make the physical properties of working fluid more superior with better cooling capacity (Cheng et al., 2013; Murshed and de Castro, 2013; Ravikumar et al., 2014). In these previous studies the emphasis tended to be put on the effect of these additives on the macroscopic properties, i.e. the heat transfer coefficient and surface temperature, with little information given on the microscopic heat transfer and mass diffusion mechanisms. The alcohol additives can avoid the potential nozzle clogging or devices corrosion caused by soluble salt additive and nanoparticles, meanwhile the corresponding lower surface tension and higher vapor pressure with respect to water will support faster bubble growth rate (Serras-Pereira et al., 2010). As a result, the

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Nomenclature

A	coefficient in Antoine equation [–]
a	attractive term in PR equation [–]
B	coefficient in Antoine equation [–]
b	co-volume in PR equation [–]
C	coefficient in Antoine equation [–]
c_v	constant-volume specific heat [J/(kg·K)]
D	mass diffusion coefficient [m^2/s]
E	internal energy [J]
F	driving force of mass transfer [–]
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. (26) [–]
k	thermal conductivity [W/m·K]
k_{ij}	coefficient in PR equation [–]
L	characteristic length scale [m]
l_{ij}	coefficient in PR equation [–]
m	mass [kg]
P	pressure [Pa]
$[P]$	parachor [–]
Q	rate of heat transfer [J]
R	bubble radius [m]
R_g	gas constant [J/(kg·K)]
r	distance from the bubble center [m]
T	temperature [K]
t	time [s]
u	velocity [m/s]
V	mole volume [m^3/mol]
x	mole fraction [–]
y	mass fraction [–]

Greek symbols

ξ	dimensionless parameter in Eq. (1) [–]
δ	boundary layer thickness [m]
ψ	diffusion coefficient in Eq. (5) [m^2/s]
α	thermal diffusivity [m^2/s]
σ	surface tension [N/m]
μ	kinematic viscosity [N·s/m^2]
γ	activity coefficient [–]
ρ	density [kg/m^3]
α_{ij}	coefficient in NRTL equation [–]
τ_{ij}	coefficient in NRTL equation [–]
φ	universal variable in Eq. (1)
χ	coefficient in Table 5 [–]
ω	acentric factor [–]
κ	coefficient in PR equation [–]

Subscripts

1, 2	more/less volatile component
c	critical
i, j	species
l	liquid
m	mass
r	radical/reduced
s	bubble surface
sat	saturation
sup	superheat
t	thermal
v	vapor
∞	far field

binary mixture of alcohol-added water is favorable as a working fluid in spray cooling, whereas the mechanism of the heat transfer enhancement has not been studied in detail yet.

Despite the high importance of multi-component spray cooling in the near future, not enough attention has been paid to investigate the microscopic mechanisms of heat transfer and mass diffusion. As one of the most important sub-phenomena in the nucleate boiling regime, the bubble dynamics basically affects the spray cooling heat transfer performance. Since the 1920s amounts of research has been conducted on mono-component bubble growth in uniformly superheated liquid or on the heating surface. Detailed overviews of several bubble growth models are summarized in Kim (2009), Lesage et al. (2014) and Wang et al. (2017). In contrast, there appears to be much fewer investigation available on multi-component bubble growth because of the complicated physical essence encountered in the boiling process. The pioneer theoretical work on spherical bubble growth in a binary mixture can be traced to the research by Scriven (1959), who derived an analytical expression with an additive term taking into account the mass diffusion. However, the inertial, viscous and surface tension effects were all neglected. Furthermore, his formulation for the growth constant is complex and the approximate versions suggested in his work are accurate only for a specific portion of the bubble growth curve (Murallidharan et al., 2018). Skinner and Bankoff (1964a, 1964b) further extended Scriven's theory from uniformly superheated and homogeneous binary mixtures to arbitrary spherically symmetric initial conditions. Subsequently Van Stralen (1968a) proposed a new dimensionless group named vaporized mass diffusion fraction to deduce an asymptotic approximation of bubble growth similar to that of mono-component bubble growth with a tuning constant. Van Stralen's expression of bubble radius was adopted in the Kandlikar's pseudo-single component heat transfer model (Kandlikar, 1997), which made attempt to link changes in the bubble growth directly to the mass diffusion of the more volatile component from the bulk liquid to the bubble-liquid interface. The model analytically predicted the liquid composition and the surface temperature at the vapor-liquid interface of a growing spherical bubble to estimate their effect on the heat transfer in pool boiling. A recent study (McNeil et al., 2017) indicated the significant underestimation of the heat transfer coefficient using the Kandlikar method because the diffusion process considered in that model produces much larger heat transfer resistance than that actually occurs.

As well known, the saturation temperature of alcohol-water mixture varies with the component concentration. The thermophysical properties of the binary mixture, such as surface tension, density, latent heat of vaporization, etc., also differ from the respective pure fluids. Furthermore, the mass diffusion of both components also affects the bubble growth in a binary liquid mixture. Thus the bubble growth of the binary mixture exhibits significantly different microscopic characteristics from the mono-component liquid. However, it is still not clear whether the bi-component bubble growth is predominant by heat transfer or mass diffusion, therefore it requires further systematic investigation. To strive for a better understanding of heat transfer and mass diffusion mechanisms during nucleation boiling of a binary mixture, the bubble growth within a superheated binary liquid is studied with liquid thermal and concentration boundary layer taken into consideration. Then the influence of component concentration and liquid temperature on the bi-component bubble growth characteristics is discussed in detail.