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Numerical simulation on single bubble behavior during Al_2O_3/H_2O nanofluids flow boiling using Moving Particle Simi-implicit method

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A B S T R A C T

In this study, regression analysis on the thermal properties of Al_2O_3/H_2O nanofluids was made firstly. The growth and departure of a single bubble behavior in Al_2O_3/H_2O nanofluid and pure water flow boiling process were then numerically simulated by an improved Moving Particle Semi-implicit method in different flow boiling conditions. The results indicate that the bubble in Al_2O_3/H_2O nanofluids grows faster and the bubble departure frequency of Al_2O_3/H_2O nanofluids is greater than that in pure water. The flow boiling heat flux is also improved by dispersing nanoparticles of Al_2O_3/H_2O in pure water. This work initially reveals that nanofluids can enhance flow boiling heat transfer from the point of view of bubble dynamics behavior. The effects of nanoparticle concentrations and diameters of Al_2O_3/H_2O nanofluids on the bubble behavior were also investigated and compared under the same flow conditions. It is found that the increasing of nanoparticle volume concentration may increase the bubble departure frequency and departure diameter, while the increasing rates of departure frequency and departure diameter are lessened with the increasing of nanoparticle volume concentration. It is suggested that the suitable nanoparticle volume concentration of nanofluid for flow boiling heat transfer enhancement should not be too large, especially regarding the negative effect of flow resistance increase due to the increasing of nanoparticle volume concentration. The interesting finding is that in the same nanoparticle volume concentration condition, the bubble departure frequency for the nanofluid with nanoparticle diameter of 29 nm shows a maximum value. The increasing of nanoparticle diameter leads to the decreasing of bubble departure diameter. It is boldly to predict that an optimal nanoparticle diameter range between 20 and 38 nm should be beneficial to flow boiling heat transfer enhancement of Al_2O_3/H_2O nanofluids.

1. Introduction

Compared with conventional heat transfer working fluid, nanofluids dispersed with suitable nano-scale metallic or nonmetallic particles can bring significant increasing of thermal conductivity. The potential applications of nanofluids in many high heat flux thermal management systems have attracted numerous research interests worldwide. The researches on nanofluids convective heat transfer, boiling heat transfer and critical heat flux are increasing exponentially every year. Nanofluids as a novel strategy to improve heat transfer characteristics of fluids by the addition of solid particles with diameters below 100 nm were proposed by Choi (1995) early in the 1990s. Very small amount of guest nanoparticles were found to provide dramatic improvements in thermal properties of base fluids. A nonlinear relationship exists between nanofluid's thermal conductivity and its concentration and temperature. Nanofluids are thus being considered as innovative and potential working fluids for heat transfer enhancement. Since You et al. (2003) first reported that the CHF of Al_2O_3/H_2O nanofluids pool boiling with particle concentrations ranging from 0 g/l to 0.05 g/l was increased by approximately 200% compared with that of pure water, nanofluids have been expected to be ideally suited for practical thermal systems where high heat flux removal is needed, such as in nuclear reactors. Thus, the characteristics of nanofluids boiling heat transfer, especially the characteristics of critical boiling, have become a hot research topic worldwide. Das

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Nomenclature

A	Heat transfer area (m^2)
c_p	specific heat at constant pressure (kJ/kg K)
d	diameter (m)
h_{fg}	latent heat (J/kg)
k	thermal conductivity (W/m k)
k_B	Boltzmann constant
M	relative molecular weight
N	Avogadro constant
Pr	Prandtl number
Q	heat (J)
Re	Reynolds number
T	Temperature (K)
Δt	time step (s)

Greek symbols

ρ	density of nanofluid (kg/m^3)
υ	dynamic viscosity (kg/m s)
σ	surface tension (N/m)
κ	curvature (1/m)
α	thermal diffusivity (m^2/s)
δ	heat conductivity thickness (m)
φ	slant angle (°)
θ	angle (°)

Superscripts

0	standard temperature of 293.15 K
Bi	bubble interior
f	base fluid
$f0$	standard state of atmospheric pressure and 273.15 K in temperature
fr	standard of freezing point
g	gas phase
i	particle number
l	liquid phase
nf	nanofluids
p	particle
w	heating surface

Abbreviations

MPS	Moving Particle Simi-implicit
MAFL	Meshless Advection using Flow-directional Local-grid
CHF	critical heat flux

et al., 2003a, 2003b conducted research on Al_2O_3/H_2O nanofluids pool boiling at atmospheric pressure and found that within a given heat flux density, the wall superheat had been increased with the increasing of nanoparticle volume concentration. The result indicated that nanoparticles deteriorated the pool boiling heat transfer. And they suggested that the trapped nanoparticles changed the heating surface characteristics during boiling. Park et al. (2009) experimental results showed that the pool boiling heat transfer coefficients of the aqueous solutions with CNTs were lower than those of pure water in the entire nucleate boiling regime. While Taylor and Phelan (2009) reported some new but limited experimental data for Al_2O_3/H_2O nanofluids that indicated that nucleate boiling incipience occurred 2–3 °C earlier, and nucleate boiling heat transfer was enhanced by 25–40%, but sub-cooled boiling was deteriorated, compared with the pure-water baseline. In contrast, other literature reported pool boiling heat transfer enhancements by nanofluids. The boiling curves for nanofluids were found in Truong (2007) experimental results to shift to the left of that for water, corresponding to higher nucleate boiling heat transfer coefficients in the two phase regime. Heris (2011) experimentally investigated the boiling heat transfer of the CuO/ethylene glycol-water (60/40) nanofluid. The results indicated that a considerable boiling heat transfer enhancement has been achieved, specifically that the enhancement had increased with increasing nanoparticles concentration and reached 55% at a nanoparticles loading of 0.5 vol. %. It is found that the current literature shows mixed or discrepant experimental results about the characteristics of nanofluids pool boiling heat transfer. This indicates, so far, that we have not yet understood the underlying mechanisms influencing boiling heat transfer of nanofluids. For most potential applications of nanofluids, flow boiling should still be an important research topic. Kim et al. (2008) carried out vertical tube flow boiling experiments of nanofluids at atmospheric pressure, low subcooling, and relatively high mass flux to investigate the CHF characteristics. A significant CHF enhancement (up to 30%) has been achieved by alumina nanoparticles as little as 0.01 Vol. %. Kim et al. (2010) conducted experiments to evaluate the possibility of enhancing CHF in flow boiling using Al_2O_3/H_2O nanofluids as working fluids vertically flowing upward in the tube under atmospheric pressure. It was verified that the dispersion stability of Al_2O_3/H_2O nanofluids during the CHF experiment was sufficient when the concentration of the nanofluids was in a range 0.001–0.5 vol. %. The CHFs of Al_2O_3/H_2O nanofluids were enhanced up to about 70%, in flow boiling for all experiment conditions. It was suggested that nanoparticles deposition on the heating surface contributed to CHF enhancement. Ahn et al. (2010) performed an experimental study on CHF enhancements of forced convective boiling of 0.01 vol. % Al_2O_3/H_2O nanofluids in a horizontal rectangular channel. The experimental results showed that, compared to that in pure water, the nanofluid flow boiling CHF was enhanced 24% and 40% with velocity of 1 m/s and 4 m/s, respectively. The heating surface was characterized before and after boiling tests, and nanoparticles deposition was observed during boiling. Kim et al. (2011) and Ahn and Kim (2012) concluded that the flow boiling CHF enhancement was caused by nanoparticles deposition on the channel inner surface.

Vafaei and Wen (2011) were the first to discuss the dual effects of nanoparticles in boiling heat transfer: (i) modification of the heating surface through nanoparticle deposition and (ii) modification of bubble dynamics by varying contact angles, departure bubble volume, and frequency. The second role may open a promising window for future nanofluid applications in micro-channel heat transfer, avoiding the high increasing in pressure drop arising from nanoparticle deposition. Xu and Xu (2012) investigated the flow boiling heat transfer with and without Al_2O_3 nanoparticles in a single micro-channel with a platinum film for bottom surface heating. The flow boiling of pure water displayed chaotic behavior due to random bubble coalescence and breakup over millisecond timescales at moderate heat fluxes. Nevertheless, the nanofluid (weight concentration of 0.2%, consisting of de-ionized water and 40 nm Al_2O_3 nanoparticles) was found to mitigate significantly the flow instability and nanoparticle deposition on the heating surface was not observed. Flow boiling of the nanofluids was always stable or quasi-stable with significantly reduced pressure drop and enhanced heat transfer. This is an interesting finding that deserves to be studied more deeply.