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Pool boiling heat transfer on the microheater surface with and without nanoparticles by pulse heating

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ABSTRACT

We study the pool boiling heat transfer on the microheater surface with and without nanoparticles by pulse heating. Nanofluids are the mixture of de-ionized water and Al_2O_3 particles with 0.1%, 0.2%, 0.5% and 1.0% weight concentrations. The microheater is a platinum surface by 50×20 μm. Three types of bubble dynamics were identified. The first type of bubble dynamics is for the boiling in pure water, referring to a sharp microheater temperature increase once a new pulse cycle begins, followed by a continuous temperature increase during the pulse duration stage. Large bubble is observed on the microheater surface and it does not disappear during the pulse off stage. The second type of bubble dynamics is for the nanofluids with 0.1% and 0.2% weight concentrations. The microheater surface temperature has a sharp increase at the start of a new pulse cycle, followed by a slight decrease during the pulse duration stage. Miniature bubble has oscillation movement along the microheater length direction, and it disappears during the pulse off stage. The third type of bubble dynamics occurs at the nanofluid weight concentration of 0.5% and 1.0%. The bubble behavior is similar to that in pure water, but the microheater temperatures are much lower than that in pure water. A structural disjoining pressure causes the smaller contact area between the dry vapor and the heater surface, decreasing the surface tension effect and resulting in the easy departure of miniature bubbles for the 0.1% and 0.2% nanofluid weight concentrations. For the 0.5% weight concentration of nanofluids, coalescence of nanoparticles to form larger particles is responsible for the large bubble formation on the heater surface. The microlayer evaporation heat transfer and the heat transfer mechanisms during the bubble departure process account for the higher heat transfer coefficients for the 0.1% and 0.2% nanofluid weight concentrations. The shortened dry area between the bubble and the heater surface, and the additional thin nanofluid liquid film evaporation heat transfer, account for the higher heat transfer coefficient for the 0.5% nanofluid weight concentration, compared with the pure water runs.

1. Introduction

Nanofluid is envisioned to describe a fluid in which nanometer-sized particles are suspended in conventional heat transfer basic fluids [1]. The thermal conductivity of the particle materials, metallic or nonmetallic such as Al_2O_3, CuO, SiO_2, and TiO_2, are typically order-of-magnitude higher than that of the base fluids even at low concentrations, resulting in significant increases in heat transfer coefficients. Single-phase liquid forced convection, as well as phase change heat transfer of nanofluids, have been widely studied [2,3].

Contradictory conclusions were reached on the boiling heat transfer of nanofluids in the literature. Bang and Chang [4] studied the boiling heat transfer of Al_2O_3–water nanofluid on the copper plate with the planar size of $4 \times 100\ mm^2$ and the thickness of 1.9 mm, and found that the effective nucleation site number is decreased due to the nanoparticles deposited on the copper surface, decreasing the nucleate heat transfer coefficients, but the critical heat flux (CHF) is increased. Golubovic et al. [5] investigated the boiling heat transfer of Al_2O_3–water and BiO_2–water nanofluid on the NiCr wire surface with the diameter of 0.64 mm and length of 50 mm. They found that the contact angle becomes smaller to enhance the critical heat flux due to the nanocoating effect on the wire surface. Kim et al. [6,7] systematically studied the effect of the porous layer on the wettability and contact angle, in which the porous layer is formed by the alumina, zirconia and silica nanoparticles on the heating surface. The critical heat flux is found to be raised, but the boiling heat transfer coefficients are not changed significantly. Dinh et al. [8] found the decreased bubble size, smaller wall temperatures, and more uniform wall temperature distribution, for the pool boiling heat transfer of Al_2O_3–H_2O nanofluid than that for the pure liquid. Wen et al. [9,10] identified the significantly increased pool boiling heat transfer coefficients of Al_2O_3–

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Nomenclature

A	heater area, m^2
D_B	diameter of the dry zone, m
D_b	bubble diameter, m
d	particle diameter, m
$\boldsymbol{F}_g$	buoyancy force, N
$\boldsymbol{F}_I$	inertia force, N
$\boldsymbol{F}_{\sigma1}$, $\boldsymbol{F}_{\sigma2}$	surface tension force, N
f	pulse frequency, Hz
g	acceleration of gravity, m/s^2
h	liquid film thickness, m
h_{lv}	latent heat of evaporation, kJ/kg
I_{film}	electric current, A
L	microheater length, m
nf	nanofluid
p	bulk osmotic pressure, Pa
p_l	pressure of the liquid, Pa
p_v	pressure of the vapor gas, Pa
pw	pure water
Q_{film}	heating power on the heater film, W
q_{film}	heat flux on the heater surface, MW/m^2
R	precision resistance, Ω
R_{Au1}, R_{Au2}	gold film resistance, Ω
R_{film}	platinum film resistance, Ω
T_{film}	heater surface temperature, °C
t	time, ms
V_1	voltages on the microheater, V
V_2	voltages in the precision resistance, V
V_{film}	voltage on the platinum film, V
W	microheater width, m
wt	weight concentration, %
x	horizontal coordinate, m

Greek symbols

δ	decay parameter
$\Delta\rho$	density difference between liquid and vapor, kg/m^3
θ	contact angle, °
κ	Debye length, m
Π_0	amplitude coefficient of disjoining pressure, Pa
Π_1	amplitude coefficient of disjoining pressure, Pa
$\Pi(h)$	disjoining pressure of a film, Pa
ρ_v	vapor density, kg/m^3
σ	surface tension, N/m
τ	pulse duration time, ms
ϕ	volume concentration, %
ϕ_2	phase of oscillations, °
w	frequency of the oscillation, Hz

Subscripts

l	liquid
v	vapor

H_2O and TiO_2–H_2O nanofluids. Liu et al. [11] studied the pool boiling heat transfer of CuO–H_2O nanofluid on the fin heat transfer surface under various pressure environments. The boiling heat transfer coefficients and critical heat fluxes are found to be increased by 25% and 50%, respectively, at the atmospheric pressure, but they are increased by 150% and 200%, respectively, under reduced pressure, for the nanofluids than those for the pure liquid. Kedzierskia and Gong [12] showed that the mixture of R134a liquid and CuO nanoparticles could significantly increase the heat transfer coefficient by 29.7%.

Several factors influence the boiling heat transfer in nanofluids. First, adding the dispersant liquid in the base fluid changes the physical properties of the base fluid. Besides, nanofluids with higher weight concentrations usually cause the particle coalescence and particle deposition on the heating surface. For the later cases, it is difficult to identify which mechanisms affect the boiling heat transfer, the nanofluids or the deposited particles on the heater surface.

In order to answer these questions, we use the nanofluids with weight concentrations of 0.1%, 0.2%, and 0.5% to perform the experiments. These concentrations cause no particle coalescence and deposition without dispersant liquid added. However, higher weight concentration of 1.0% was also used, which results in the particle deposition on the heater surface. A platinum microheater was used, which was driven by a pulse voltage generator. Three types of bubble dynamics were identified. The bubble dynamics is observed by a high speed camera bonded with a microscope. Physical explanations are given for the three types of bubble dynamics. It is well known that the periodic bubble behavior driven by pulse voltage generator has been widely used for various microfluidic actuators. The key issue for such kind of actuators is the high microheater temperatures during the heating stage. Mixing nanoparticles with pure liquid is helpful to maintain low microheater temperatures, preventing the microheater from damage due to the high temperature. This study identifies that the nanofluids with uniformly distributed nanoparticles enhance the pool boiling heat transfer, corresponding to the low nanofluid concentrations such as smaller than 0.5%. However, high nanofluid weight concentration such as larger than 1.0% has poorer boiling heat transfer performance than the low weight concentrations, due to the deposited particles on the heater surface, but is still better than the pure water runs.

2. Description of the experiment

2.1. Preparation of nanofluids

The Al_2O_3 nanoparticles have spherical shape with the average diameter of 13 nm. These particles are dispersed in the de-ionized water by the ultrasonic oscillation method. Four weight concentrations of 0.1%, 0.2%, 0.5% and 1.0% are used, without dispersant fluid involved. The nanoparticles before the ultrasonic oscillation treatment are coalesced together to form the floc shape, as shown in Fig. 1a. On the contrary, the nanoparticles after the ultrasonic oscillation treatment is uniformly distributed for the weight concentrations of 0.1%, 0.2%, and 0.5%. Fig. 1b shows that no coalescence phenomenon is observed for the 0.2% weight concentration. However, for the weight concentrations of 1.0%, the particle coalescence is observed without the dispersant fluid involved (see Fig. 1c). In this study, because the nanoparticles have small size in the order of 10 nm, they are not settled down on the heater surface for the weight concentrations of 0.1%, 0.2%, and 0.5%. As observed in Fig. 1d, the heater surface is clean after several days of operation of experiments. However, nanoparticles indeed deposit on the heater surface and accumulate there after one day operation of experiments for the 1.0% weight concentration, as shown in Fig. 1e.