



Nanoparticle layer detachment and its influence on the heat transfer characteristics in saturated pool boiling of nanofluids



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ABSTRACT

In nucleate pool boiling of nanofluid, nanoparticles suspended in liquid are deposited to form nanoparticle layer on the heated surface. As a result, surface properties are changed and the critical heat flux (CHF) is usually enhanced. However, since adhesion of the nanoparticle layer to the heated surface is not necessarily strong, partial detachment of the nanoparticle layer frequently occurs during nucleate boiling. In this study, peeling test was conducted for the nanoparticle layer formed during nucleate boiling of the water-based nanofluids to measure the adhesion force. The material of the heated surface was copper, and TiO_2 , Al_2O_3 and SiO_2 were used as the nanoparticle material. It was found that the adhesion force is highly dependent on the nanoparticle material; it was greatest for SiO_2 and weakest for TiO_2 in the present experiments. Then, saturated pool boiling curves were obtained using the damaged heated surfaces after the peeling. For the nanoparticle-layer coated surfaces without peeling, the heat transfer coefficient (HTC) was lower and CHF was higher than those for the bare surface. It was shown that with an increase in the mass of the nanoparticles removed by peeling, the decrease of HTC and the increase of CHF were mitigated. Even higher HTC values and a lower CHF value than those for the bare heated surface were measured for significantly damaged surfaces.

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1. Introduction

Nanofluid is the liquid in which nanometer-sized solid particles are suspended in a base liquid such as water or oil. It has been reported that in nucleate pool boiling in nanofluid, the heat transfer coefficient (HTC) and the critical heat flux (CHF) can significantly be different from those in the pure liquid containing no nanoparticles. Extensive reviews by several investigators showed that the HTC in nanofluids can be enhanced, deteriorated, or unchanged depending on the experimental conditions, whilst the CHF is usually enhanced greatly [1–9]. It is hence considered that boiling heat transfer of nanofluid can effectively be used for the cooling of high-power-density devices such as the next-generation CPU and the inverters for fuel-cell and electric vehicles [10,11]; it may also be applied to the emergency cooling of nuclear reactors [12,13].

During nucleate boiling in nanofluid, nanoparticles are deposited to form a thin layer on the heated surface. The formation of the nanoparticle layer is considered as a main mechanism causing the difference of the heat transfer characteristics since the surface

properties such as the roughness, the wettability and the wickability are totally changed [14–18]. For instance, Kim et al. [19] measured the contact angle of the nanoparticle-deposited heated surface to report that the contact angle decreased noticeably after the nucleate boiling in nanofluid and strong correlation was present between the surface wettability and the boiling heat transfer. Kim and Kim [20] showed that the CHF in the nanofluid can be correlated using the contact angle and the capillarity of the heated surface. It should however be noted that adhesion of the nanoparticle layer to the heated surface is not necessarily strong. Okawa et al. [21] found partial detachment of the TiO_2 nanoparticle layer from the heated surface during nucleate boiling in distilled water. They reported that the CHF enhancement by the nanoparticle layer was reduced when the nanoparticle layer detachment took place. Zuhairi et al. [22] also found the partial detachment of the nanoparticle layer for the TiO_2 - and SiO_2 -water nanofluids. Peculiar time-variation of the wall superheat was observed for these heated surfaces. It was discussed that such time-variation was related to the nanoparticle layer detachment. These experimental results show that the nanoparticle layer detachment may occur in the nucleate boiling of nanofluid and it can influence the boiling heat transfer characteristics.

Nanoparticles are not expensive and nanoparticle layer can easily be fabricated on the heated surface. It is hence expected that

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Nomenclature

h	heat transfer coefficient
q_c	critical heat flux
q_w	wall heat flux
M	mass of nanoparticles remaining on the heated surface
M_0	total mass of nanoparticle layer
M_p	mass of nanoparticles peeled from the heated surface
F_{ad}	adhesion force
t_b	boiling time

<i>Greek symbols</i>	
ΔT_w	wall superheat
θ	contact angle

<i>Subscript</i>	
mean	mean value

<i>Other notation</i>	
CV(x)	cumulative value of x

the nanoparticle-deposited surface can be used as the enhanced heat transfer surface of economic advantage. However, sufficiently tight adhesion is required for the nanoparticle layer in this case. Also, in the application to the emergency cooling of nuclear reactor, temporary change of the heat transfer characteristics may lead to unexpected outcome. However, no quantitative experimental information is available for the adhesion force of the nanoparticle layer and the influence of the nanoparticle layer detachment on the boiling heat transfer characteristics. In view of this, in this work, peeling test is conducted for the nanoparticle layers formed on the heated surface. As the typical materials, copper is used as the material of the heated surface and titanium-dioxide (TiO₂), alumina (Al₂O₃), and silica (SiO₂) are used as the nanoparticle material. Using the damaged heated surface after peeling, boiling curves are obtained to investigate the influence of the nanoparticle layer detachment on the HTC and CHF in the nucleate pool boiling of distilled water.

2. Experimental method

2.1. Experimental apparatus

Photograph and schematic diagram of the experimental apparatus are depicted in Fig. 1(a) and (b), respectively. The copper block containing nine cartridge heaters was set on the bottom plate of the cylindrical experimental vessel. The end face of the copper block of 20 mm in diameter was used as the heated surface. Each cartridge heater was 7.3 mm in diameter and 45 mm in length, and its maximum power was 100 W. The maximum achievable heat flux is hence calculated 2.87 MW/m²; the power of the cartridge heaters was controlled using a volt slider. To reduce the heat loss from the side wall of the copper block, it was covered by the stainless steel jacket and the space between the copper block and the jacket was filled with glass wool. The copper block and the jacket were bonded smoothly by means of electron beam welding. The copper block contained four calibrated type-K thermocouples accurate to within ± 0.1 – 0.3 K on the central axis to calculate the wall superheat ΔT_w and the heat flux q_w and to shut down the system when the CHF condition was reached. From the error propagation analyses, the measurement uncertainties of ΔT_w and q_w were estimated within ± 2 K and ± 58 kW/m², respectively.

The experimental vessel was 144 mm in diameter and 170 mm in height; it was mainly made of transparent polycarbonate but the bottom plate was made of stainless steel. The elevation of the heated surface was 35 mm from the bottom of the vessel and the water level was 110 mm as shown in Fig. 1. During the experiments reported in this paper, the side wall of the vessel was covered with a thermal insulation material to reduce the heat loss. The immersion heater in the vessel was used to heat up the subcooled liquid and then maintain the liquid temperature at the saturation temperature. The liquid temperature was measured

10 mm above the heated surface using a type-K thermocouple accurate to within ± 0.3 K. A Dimroth condenser was equipped on the top lid of the vessel to keep the mass of test liquid in the vessel constant. Since the vessel was open to the atmosphere through the condenser, the pressure in the vessel was close to the atmospheric pressure.

2.2. Formation of the nanoparticle layer on the heated surface

As the material of nanoparticles, TiO₂ (Aeroxide TiO₂ P25; mixture of 80% anatase and 20% rutile), Al₂O₃ (Aeroxide Alu C), and SiO₂ (Aeroxide 90 G) were used. To prepare the nanofluid, 300 mg of nanoparticles were weighed using an electronic balance accurate to within ± 0.07 mg (HR-202i, A&D Co., Ltd.). The weighed nanoparticles were then mixed with 200 ml of distilled water and ultrasonic excitation at 430 kHz was performed for 3 h using an ultrasonic bath (QR-003, Kaijo Co., Ltd.). These procedures were considered sufficient to ensure stable particle dispersion since no noticeable particle sedimentation was found even 24 h after the nanofluid preparation. Fig. 2 shows the particle size distributions in the nanofluids that were measured using a particle diameter analyzer (FPAR-1000, Otsuka Electronics Co, Ltd.). It can be seen that the particle size distributed within 80–800 nm and greater than the mean primary particle sizes reported by the manufacturer (21 nm for TiO₂, 13 nm for Al₂O₃, and 20 nm for SiO₂); this results suggest that nanoparticles formed clusters in the nanofluids [14,15]. After preparing the nanofluid, the heated surface was polished using metal polishing paste and cleaned using acetone. The surface wettability was then measured using a contact angle goniometer (PG-X, Fibro System AB) to confirm that the contact angle was within the prescribed range of $90 \pm 5^\circ$.

After setting the heating device on the experimental vessel, 1300 ml of distilled water was supplied and saturated pool boiling was initiated in the vessel using the heating device and the immersion heater; here, the heat flux of the heating device q_w was set at 650 kW/m². After keeping saturated boiling for about 20 min for degassing, 200 ml of nanofluid was added to the test liquid. Since 300 mg of nanoparticle was contained, the nanoparticle concentration of the test liquid was calculated 0.2 kg/m³. Nucleate boiling was maintained for 60 min to form the nanoparticle layer on the heated surface. The photographs of the original bare surface and the 3 nanoparticle-layer coated surfaces are presented in Fig. 3 (a)–(d), respectively. Appearance of the Al₂O₃ nanoparticle-deposited surface (Fig. 3(c)) was relatively similar to that of the original surface (Fig. 3(a)), but the TiO₂ and SiO₂ nanoparticle-deposited surfaces (Fig. 3(b) and (d)) were whitish in color.

2.3. Experimental procedure

As shown in Fig. 4, the following three types of measurement were performed after the preparation of the nanoparticle-

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