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Experimental studies on CHF enhancement in pool boiling of nano-fluids

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1. Introduction

Recently, You et al. [1] and Vassallo et al. [2] have been independently obtained the experimental results that nano-fluids makes the dramatic increase in CHF. But they could not explain the abnormal CHF enhancement of nano-fluids with any existing models of CHF. Kim et al. [3] performed the experimental studies on pool boiling heat transfer in TiO_2–water nano-fluids under atmospheric pressure. From the experimental results, they concluded that the unusual CHF enhancement using nano-fluids was due to the effect of nanoparticles coated on heating surface, not the change in physical properties of cooling liquid.

In this study, the characteristics of pool boiling CHF of water based nano-fluids with titania nanoparticles are investigated on a NiCr wire heater at atmospheric pressure. And then to understand the mechanism of CHF enhancement due to the nanoparticle coating, the modified surface subsequent to the pool boiling CHF experiment is characterized with parameters closely related to CHF: surface wettability, surface roughness, and capillary wicking height. The contribution of each parameter to CHF enhancement of nano-fluids is discussed.

2. Pool Boiling CHF Experiment

Pool boiling CHF experiments of TiO_2–water nano-fluids are carried using a smooth, bare NiCr wire. And the CHF values of pure water on a nanoparticle-coated heater are measured in order to separately estimate the role of nanoparticle surface coating on the CHF enhancement of nano-fluids. The details of setup and procedure for the pool boiling experiment were described in our previous paper [3].

3. Characterization of Heater Surface

To analyze the effect of surface properties, changed due to nanoparticle surface coating, on CHF enhancement of nano-fluids, this study quantitatively characterizes the heater surface using the surface roughness (Ra) and the capability for capillary wicking (Lc). Heater wires are identified 'NFB' and 'WNC' respectively, named using the initial letters of the composition of working fluids and heater surface characteristics (e.g. WNC for water on nanoparticle-coated heater).

2.1. Visualization of heater surface

After each pool boiling CHF experiment, the heater surface is examined using scanning electron microscope (SEM). The SEM observation makes it possible to identify the overall shape as well as the morphology (micro structures) of the heater surface.

2.2. Surface roughness (Ra) measurement

It is impossible to measure the surface roughness of a small wire with 0.2 mm diameter using conventional surface profiler. Therefore a new method to measure the surface roughness of the thin wire is adopted. First, SEM image focused on the side edge of the wire is captured with magnification of 1200. Second, the profile of the boundary between the wire heater and background is extracted by the image processing software. And then, the 2-dimensional profile is digitalized using the scale bar in the capture image. The digitalized profile contains about 470 points with 0.21 μm spacing along the wire. Finally, the surface roughness of each wire heater is calculated using following equation:

$$R_a = \left(1/S\right)\int_0^S \left|Y(X)-\overline{Y}\right| dx \approx \frac{1}{N}\sum_{i=1}^{N}\left|Y_i-\overline{Y}\right| \qquad (1)$$

2.3. Capillary wicking height (Lc) measurement

A nanoparticle-coated NiCr wire is vertically fixed (gravitational direction) and the bottom of the wire is immersed in the reservoir of water. The heights of the liquid column are estimated not only at the maximum point within several seconds but also at the saturated state after several minutes. Since the environment is not the saturated condition, the evaporation from the wire to the environment exists.

3. Results

Figure 1 shows a comparison of CHF enhancements of nano-fluids with that of pure water on the nanoparticle-coated heater. For all particle concentrations, the CHF enhancements of pure water on the nanoparticle-coated heater are not less large than those of nano-fluids. This result clearly reveals that the unusual CHF enhancement using nano-fluids is due to the effect of nanoparticles coated on heating surface.

Figure 2 shows the values of Ra measured on the heater wires corresponding to the various particle concentrations. Ra of NFB and WNC increased with increasing concentration. With no doubt, the change of Ra is due to the nanoparticle surface coating. The increasing Ra indicates that the nanoparticle surface coating is not uniform, but makes larger and more fractal structures as the particle concentration increases.

The photographic observation in Fig. 3(c) shows the departing of the large vapor mushroom after merging of bubbles growing on the nanoparticle-coated wire at the high heat flux near CHF. Though the heater is almost covered with the growing bubbles, the coated wire has been effectively preventing departing from the nucleate boiling region. This fact indicates that the supplying of liquid on the heater wire is still enough to endure the high heat flux.

The additional liquid can be supplied by the liquid suction due to capillary wicking on the nanoparticle coated wire. Fig. 4 shows the capillary wicking height due to microstructures on the heater surface. In the measurement of capillary wicking height (Lc), the heater wires for the particle concentration below 10^{-4}% didn't create a liquid rise due to capillary wicking, because the micro-structures of the heater surface at those concentrations were not enough to act as a micro-flow-pass. However Lc of 1.2 mm is observed at the concentration of 10^{-3}%, and then Lc steeply increases to 4.7 mm at 10^{-2}% and to 5.9 mm at 10^{-1}%. This behavior of Lc is a common factor for both surfaces.

REFERENCES

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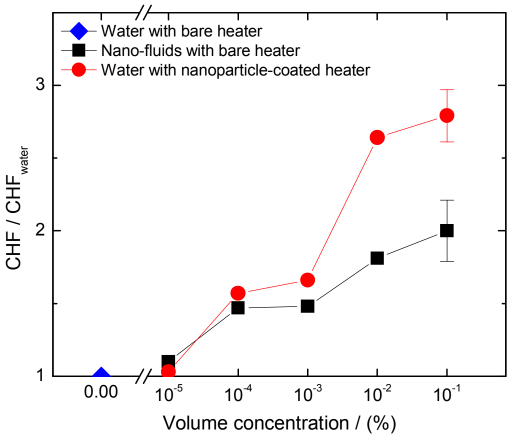


Figure 1. A comparison of CHF of nano-fluids on bare heater with that of pure water on nanoparticle-coated heater

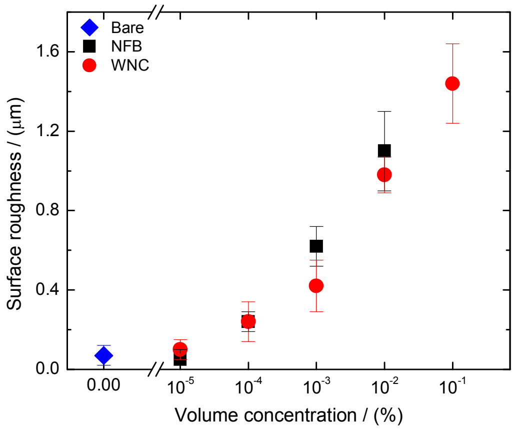
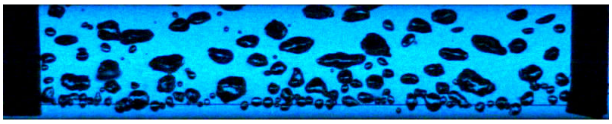
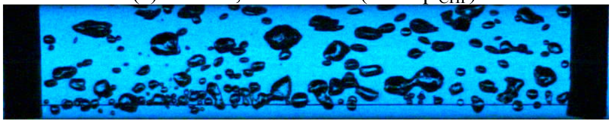


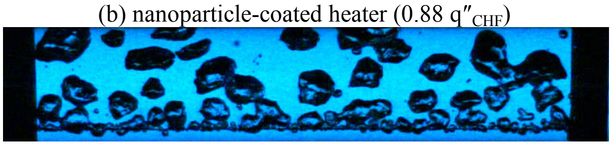
Figure 2. Dependancy of the surface roughness on the particle concentration



(a) smooth, bare heater (0.88 q''_{CHF})



(b) nanoparticle-coated heater (0.88 q''_{CHF})



(c) nanoparticle-coated heater (2.07 q''_{CHF})

Figure 3. Photographs of pool boiling of pure water on the different heater wire

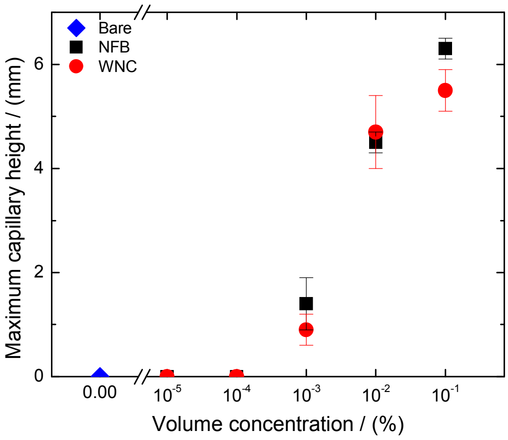


Figure 4. Dependancy of the maximum capillary wicking height on the particle concentration