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Effects of the improved surface wettability and capillarity of nanoparticle deposition layer on CHF enhancement in pool boiling of nanofluids

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1. Introduction

Nanofluids, which contain uniformly and stably dispersed nanoparticles, have different heat transfer properties than pure fluid. Nanofluids exhibit an abnormal enhancement of the critical heat flux (CHF) when used as a working fluid in pool boiling. It is a very attractive phenomenon as a scientific subject, as well as to industrial application like cooling of equipments with high thermal density. Since the pioneering exploration of You et al. [1], there have been several investigations to understand the pool boiling CHF enhancement of nanofluids. However they only confirmed the outstanding CHF enhancement of nanofluids and it was insufficient to fully understand the mechanism of CHF enhancement of nanofluids.

Many investigators observed an intensive deposition of nanoparticles during boiling of nanofluids and conjectured that the deposition might cause CHF enhancement of nanofluids. Recently, Kim et al. [2] clearly showed that the main cause of CHF enhancement of nanofluids was the change of surface properties of the heater due to the nanoparticle surface coating formed during pool boiling. In their experiments, significant enhancement of CHF using nanofluids was sufficiently reproduced by CHF of water on the nanoparticle-deposited surface. Therefore, the CHF enhancement of nanofluids is a kind of interfacial phenomena including the non-hydrodynamic aspect of surface-liquid interaction. An understanding of the underlying mechanism must be sought to determine the effect of a nanoparticle-deposited surface on the CHF.

The objective of this study is to examine the relationship between the enhancement of the CHF performance due to nanoparticle surface deposition and the changes in the surface characteristics such as surface wettability and capillarity, which are closely related to rewetting of a dry patch during boiling. This will provide insight into how the nanoparticle deposition produces the significant CHF enhancement in pool boiling.

2. Experiment

We prepared nanoparticle-deposited surfaces to study the relationship between the CHF and the surface characteristics of nanoparticle deposition layers. The boiling experiments used to prepare the test surfaces were performed with electrically heated nichrome (NiCr) and Ti wires (115 mm in length; 0.2 mm and 0.25 mm in diameter, respectively) that were horizontally immersed in various water-based nanofluids. Three nanoparticles, Al_2O_3, SiO_2, TiO_2, and Ag, were used to make the nanofluids, with volume concentrations ranging from 10^{-5} to 10^{-1}%. We then performed a pool boiling experiment using pure water and the prepared nanoparticle-deposited surfaces. The nanoparticle deposition layers were characterized based on their surface wettability and maximum liquid rise due to capillary wicking, which are the significant properties of boiling surface influencing CHF. Finally, we correlated the CHF data using the properties of the nanoparticle-deposited surface, and discussed the mechanism of CHF enhancement of nanofluids.

3. Result and Discussion

We examined how well surface wettability of nanoparticle deposition layer can correlate CHF enhancement of pure water on the nanoparticle-coated surface. Figure 1(a) shows a relationship between the measured CHF value and contact angle of water on nanoparticle-coated surface. With decreasing contact angle from about 70° to about 20°, CHF increased gradually. Interestingly, tendency of the experimental data was correctly predicted by the prediction of Kandlikar [3] including the surface-liquid interaction effects through the dynamic receding contact angle. However, at small contact angles near 20°, CHF increased additionally without further reduction of apparent contact angle. And the maximum value extremely exceeded the prediction of Kandlikar [3]. Resultantly, much of the outstanding CHF enhancements on the nanoparticle-coated heaters were attributed to the decreases of contact angle (or improvement of surface wettability), but there were the exceptional enhancements of CHF which could not be explained only using the effect of contact angle.

Figure 1(b) shows a comparison of the surface morphology of two TiO_2 nanoparticle-coated wires having similar apparent contact angle of 20° but making quite different CHF values of 2600 kW/m^2 (A) and 1500 kW/m^2 (B). The surface with very high CHF had greatly enhanced microstructures which can induce the liquid flow due to capillary wicking effect, but another had a relatively smooth surface.

The effect of a capillary porous layer on pool boiling CHF has been analyzed by Tehvor [4]. His analysis was from the macrolayer concept based on Haramura and Katto's [5] CHF model, which considers the formation and evaporation of a macrolayer under a bubble. He hypothesized that liquid suction due to capillary wicking helps to supply bulk liquid to heating surface, so boiling crisis can be effectively delayed.

Figure 2 shows dependencies of area-corrected CHF on the amount of liquid suction due to capillary wicking. The capillary wicking amount is given by

$$\varepsilon \cdot A_c \cdot L_{c,\max} \qquad (1)$$

where ε and A_c is porosity and cross section area of nanoparticle surface coating, respectively. And porosity was assumed to be 0.5 without any verification. The cross section areas were estimated using the diameters of the nanoparticle-coated wires. In addition, the heat flux was also corrected using the surface area increased due to the nanoparticle coating. The slops of almost all cases were consistent except for the Al_2O_3 with very nominal rise of water. Resultantly, it was demonstrated that the abnormal enhancement of pool boiling CHF on the nanoparticle-coated wires was attributed not only to high surface wettability but also to the additional liquid supply due to capillary wicking.

4. Conclusion

In order to understand the mechanism of the unusual CHF enhancement in pool boiling of nanofluids, the effect of the surface wetability and capillarity of the nanoparticle deposition layer on the CHF was examined. The deposition of nanoparticles improved the surface wettability, and it also caused capillary wicking on a porous surface where the supplied liquid can effectively delay the irreversible growth of a dry patch and the CHF during pool boiling heat transfer. Our study demonstrates that the outstanding CHF enhancement in nanofluids is the consequence of both the improved surface wettability and the capillarity of the nanoparticle deposition layer.

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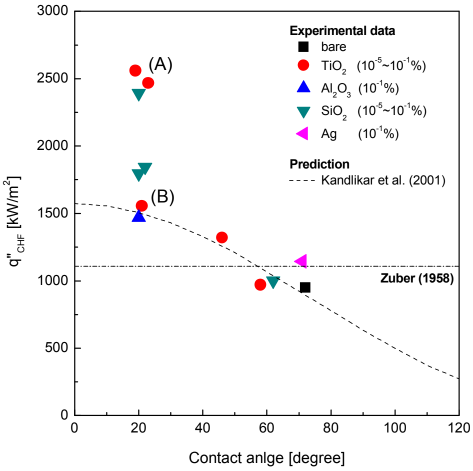
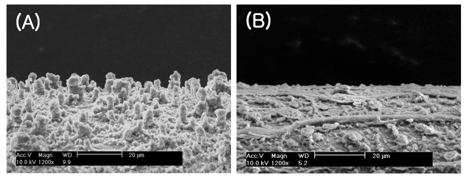


(a)



(b)

Figure 1. Effect of surface wettability on CHF: (a) dependency of CHF value on contact angle of water on nanoparticle-coated surface; (b) comparison of two coated wires of (A) 0.1% and (B) 0.001%.

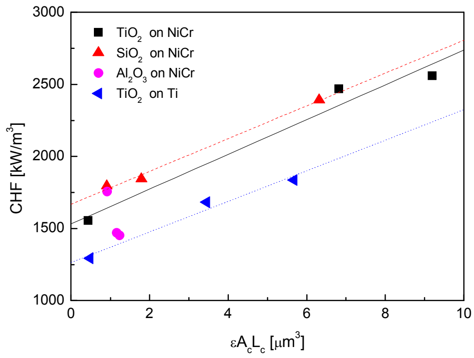


Figure 2. Effect of capillary wicking amount on CHF.