

Technical Note

Effect of nanoparticles on CHF enhancement in pool boiling of nano-fluids

Hyungdae Kim^a, Jeongbae Kim^b, Moo Hwan Kim^{a,*}

^a Mechanical Engineering Department, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang 790-784, Republic of Korea

^b Korea Institute of Energy Research, Daejeon 305-343, Republic of Korea

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Abstract

To investigate the characteristics of CHF (Critical Heat Flux) enhancement using nano-fluids, pool boiling CHF experiments of two water-based nano-fluids with titania and alumina nanoparticles were performed using electrically heated metal wires under atmospheric pressure. The results showed that the water-based nano-fluids significantly enhanced CHF compared to that of pure water. SEM (Scanning Electron Microscopy) observation subsequent to the pool boiling experiments revealed that a lot of nanoparticles were deposited on heating surface during pool boiling of nano-fluids. In order to investigate the role of the nanoparticle surface coating on CHF enhancement of nano-fluids, pool boiling CHF of pure water was measured using a nanoparticle-coated heater prepared by pool boiling of nano-fluids on a bare heater. It was found that pool boiling of pure water on the nanoparticle-coated heater sufficiently achieved the CHF enhancement of nano-fluids. It is supposed that CHF enhancement in pool boiling of nano-fluids is mainly caused by the nanoparticle coating of the heating surface.

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1. Introduction

Recently, researchers have attempted to enhance CHF using nano-fluids, a new kind of heat transfer fluid in which nanoparticles are uniformly and stably dispersed. First, You et al. [1] measured the CHF in pool boiling on a flat square copper surface immersed in water–Al₂O₃ nano-fluids at the sub-atmospheric pressure of 2.89 psia and showed that nanoparticles at concentrations as low as 10⁻³ g/l (~10⁻⁴ vol.%) could dramatically increase CHF. They concluded that the unusual CHF enhancement of nano-fluids could not be explained by any existing model of CHF. Vassallo et al. [2] performed experimental studies on pool boiling heat transfer in 0.5 vol.% water–SiO₂ nano-fluids using a 0.4 mm wire heater under atmospheric

pressure. CHF increased remarkably, and a thick (0.15–0.2 mm) silica coating was observed on the wire heater. Most recently, Bang and Chang [3] showed CHF enhancement in pool boiling on a flat plate heater immersed in water–Al₂O₃ nano-fluids under atmospheric pressure. From the roughness change of the heater surface before and after experiments, they hypothesized that the reason for CHF performance change might be due to surface coating of the heater with nanoparticles.

In order to study possible effects of nanoparticles on CHF enhancement in pool boiling of nano-fluids, pool boiling CHF values are measured and compared from (a) a bare heater immersed in nano-fluids and (b) a nanoparticle-coated heater, prepared by deposition of suspended nanoparticles during pool boiling of nano-fluids, immersed in pure water. In addition, the heater surface after each experiment was studied using SEM in order to investigate the change of the surface microstructure and topography.

* Corresponding author. Tel.: +82 54 279 2165; fax: +82 54 279 3199.
E-mail address: mhkim@postech.ac.kr (M.H. Kim).

2. Experimental setup and procedure

The main test pool consists of a 250 × 140 mm × 250 mm rectangular Pyrex glass vessel and a 30 mm thick Teflon cover. The test pool was pre-heated on a Corning hot plate and the pool temperature was measured with a Pt-100 Ω RTD sensor. The reflux condenser cooled with tap water prevented the loss of vapor from the test chamber. Accordingly, the volume concentration of the working fluid did not change during the pool boiling. The opening on the top of the condenser maintained atmospheric pressure inside the chamber

and the pool temperature was naturally adjusted to the saturated temperature (100 °C). As boiling surfaces, horizontally suspended metal wires were used: NiCr wire with 0.2 mm diameter and Ti wire with 0.25 mm diameter.

The experiment was performed by increasing electric power supplied to the wire, using a HP agilent 6575A DC power supply (120 V/18 A). Close to the CHF, the power was increased in small steps. When the CHF was reached, the resistance of the wire heater sharply increased and the heater was instantaneously broken. The CHF was calculated using the current and voltage drop, measured by

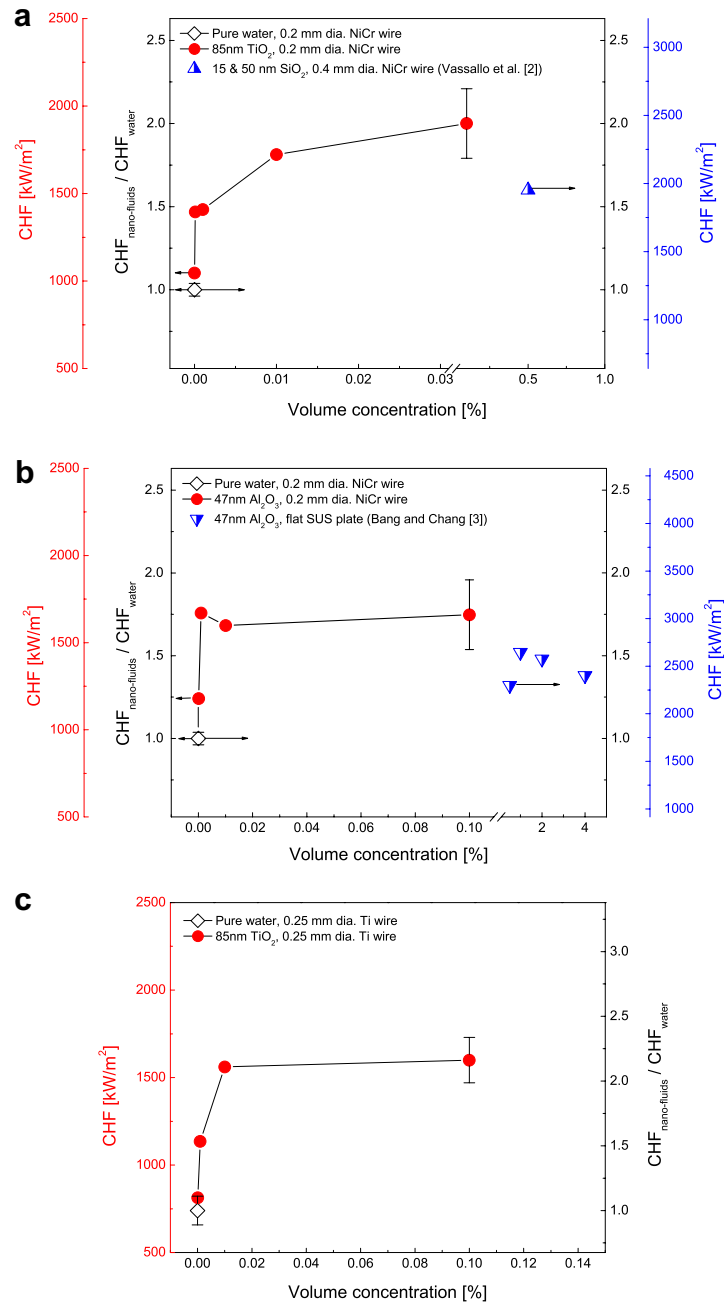


Fig. 1. CHF of pure water and nano-fluids: (a) CHF of water-TiO₂ nano-fluids on NiCr wire; (b) CHF of water-Al₂O₃ nano-fluids on NiCr wire; (c) CHF of water-TiO₂ nano-fluids on Ti wire.

a HP agilent 34970A data acquisition system, immediately before the steep increase of heater resistance:

$$\dot{q}_{CHF}'' = V_{\max} I_{\max} / \pi DL \quad (1)$$

3. Results and discussion

3.1. Pool boiling CHF experiment of nano-fluids

Two kinds of nano-fluids were used in this work: water–titania (TiO_2) and water–alumina (Al_2O_3) nano-fluids. Titania nanoparticles were produced by the Sol–Gel process of Advanced Nano Product Corporation and alumina nanoparticles were manufactured by the patented physical vapor synthesis (PVS) Process of Nanophase Technologies Corporation. The mean particle sizes of the nanoparticles were 85 nm and 47 nm respectively. Nano-fluids were prepared by dispersing nanoparticles into water as a base fluid. For stable dispersion of nanoparticles, 3 h of ultrasonic excitation were performed without additive. Solutions with the desired volume concentration of nanoparticles were obtained by mixing the appropriate amounts of distilled water and nanoparticles. Vassallo et al. [2] have reported the significant increase of CHF using 0.5% water– SiO_2 nano-fluids. On the other hand, You et al. [1] also have observed the vigorous CHF enhancement using water– Al_2O_3 nano-fluids at concentrations as low as $10^{-4}\%$. Thus, in order to cover quite different concentrations of nano-fluids in previous researches, the nano-fluids used in this work had logarithmically different concentrations ranging from $10^{-5}\%$ to $10^{-1}\%$.

Fig. 1 shows pool boiling CHF of pure water and nano-fluids, and a value of CHF is a mean of experimental results above three. For the increase of the particle concentration, CHF of nano-fluids in all cases (TiO_2 on NiCr, Al_2O_3 on NiCr, and TiO_2 on Ti) sharply increases at the small concentrations, and then becomes saturated with the significant enhancements of CHF. The saturation phenomenon of CHF using nano-fluids are consistent with the results to have been reported by You et al. [1] from the pool boiling CHF experiments of water– Al_2O_3 nano-fluids under the reduced pressure.

According to the combinations of nano-fluids and heater material, the quantitative degrees of CHF increases are different. CHF of water– TiO_2 nano-fluids from a NiCr heater increases up to 148% of the value of pure water at particle concentrations below $10^{-3}\%$, and then becomes saturated at about 200% at $10^{-1}\%$. This tendency of CHF of water– TiO_2 nano-fluids from a NiCr heater is very similar to CHF enhancement of water– TiO_2 nano-fluids from a Ti heater, and however the saturated values of the enhancement are different because CHFs of pure water are different on NiCr and Ti wires. On the other hand, CHF of water– Al_2O_3 nano-fluids on a NiCr heater has a little different behavior from the results of water– TiO_2 nano-fluids on NiCr and Ti wires. At the small concentration of $10^{-3}\%$, the CHF enhancement is much higher than those of TiO_2 nano-fluids

and attains the maximum of 176% without more increase though increasing particle concentration to $10^{-1}\%$.

In the comparisons between the saturated CHF values of $10^{-1}\%$ nano-fluids in the present work and those of previous researches with large particle concentrations, the CHF increases of all nano-fluids are consistent in the absolute values with approximately 700–900 kW/m^2 even though there are many differences in conditions of nanoparticle (material and size) as well as heater (material and geometry). But the enhancements relative to CHF of pure water are presented with large deviations due to the differences in pool boiling CHF values of pure water as given in Fig. 1.

Fig. 2 shows the microstructure and topography of the heater surface modified by the deposition of suspended nanoparticles during the pool boiling of nano-fluids. It is impossible to discern the differences between the upside and downside of the heating wire in the test pool in terms of the deposition of nanoparticles. This means that the formation of nanoparticle surface coating is mainly attributed to the nucleation of vapor bubbles on the cylindrical wire,

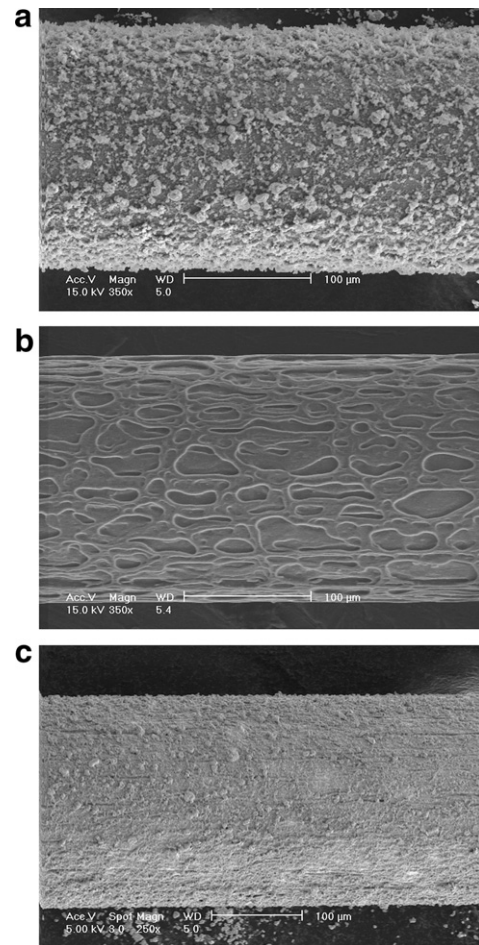


Fig. 2. A comparison of nanoparticle-coated heaters generated by pool boiling CHF experiments of 0.01% nano-fluids: (a) TiO_2 nanoparticle-coated NiCr wire with 0.2 mm dia. ($\times 350$); (b) Al_2O_3 nanoparticle-coated NiCr wire with 0.2 mm dia. ($\times 350$); (c) TiO_2 nanoparticle-coated Ti wire with 0.25 mm dia. ($\times 250$).

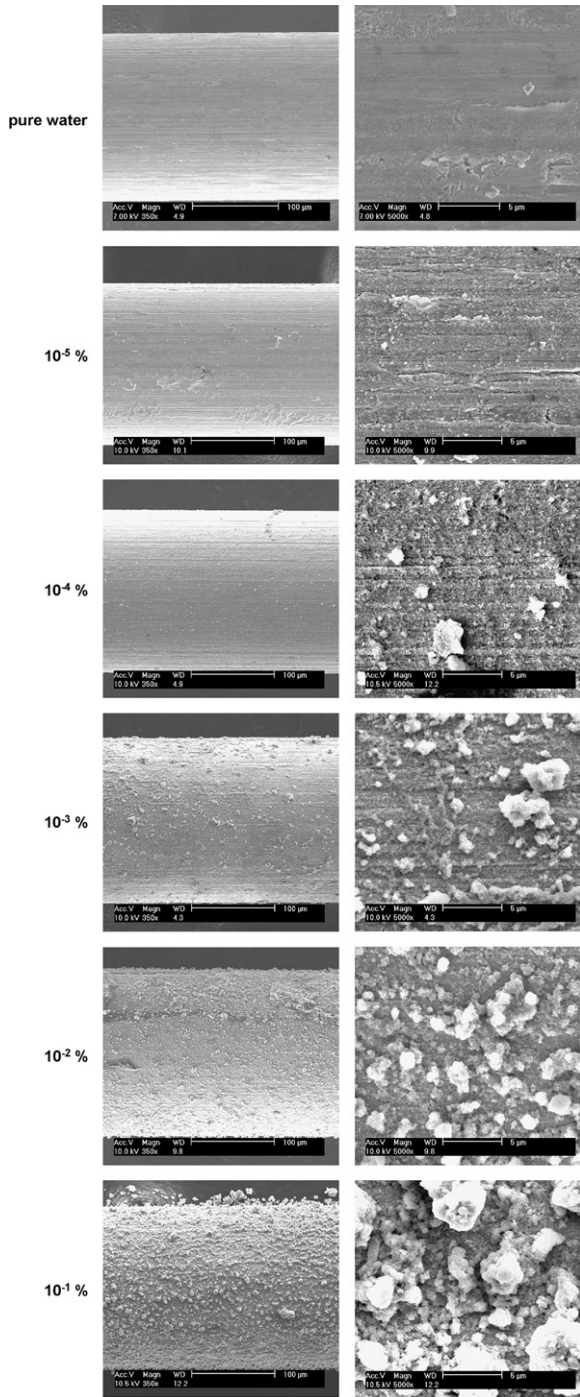


Fig. 3. TiO₂ nanoparticle-coated NiCr wire after pool boiling CHF experiment of nano-fluids with different particle volume concentrations.

not to the gravitational sedimentation of nanoparticles. In fact, in the pool boiling CHF experiments, the coating of nanoparticles on the heater wire matured within the small time duration due to very frequent and numerous nucleations of bubbles.

The surface modifications due to nanoparticle surface coating are quite different according to the kind of nanoparticle dispersed in nano-fluids, but not to the material of heater as shown in the comparison of Fig. 2a–c. Moreover the

characteristics of nanoparticle surface coating are highly dependent on the concentration of nano-fluids as shown in Fig. 3. In the case of nano-fluids with the lowest particle concentration, 10⁻⁵%, the heating surface displays only a nominal change. However, as the concentration increases, surface deposition of the nanoparticles thickens (~6.5 μm) and more micro-sized structures are formed on the heating surface due to aggregation of titania nanoparticles.

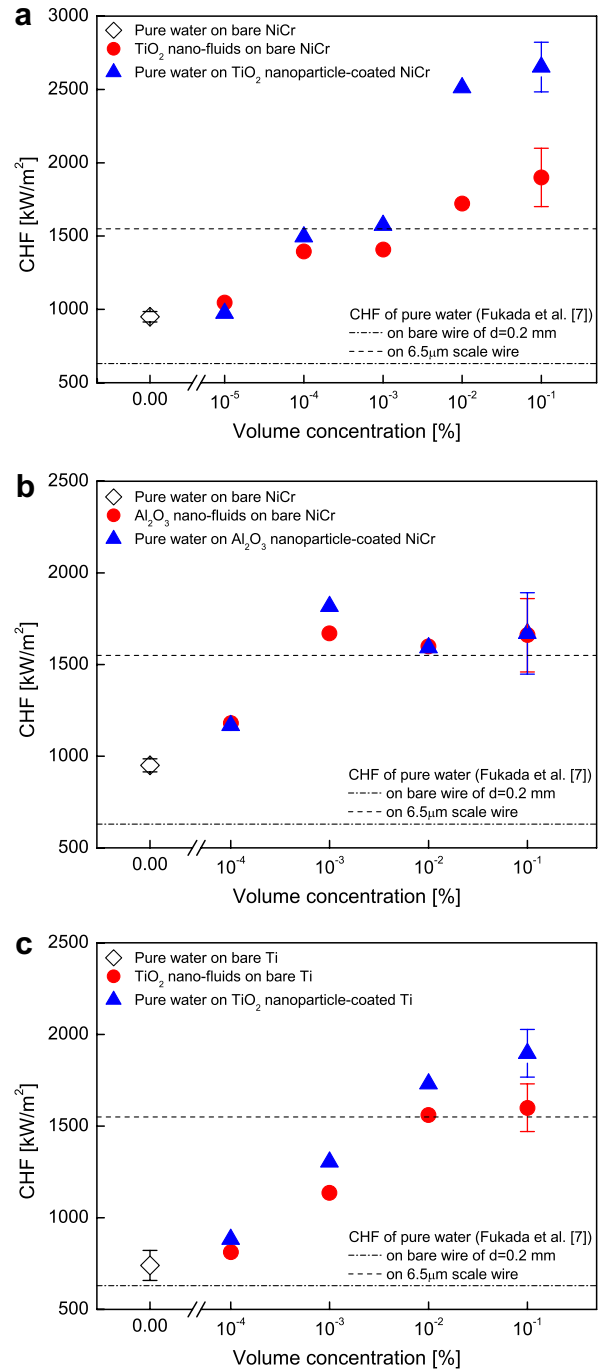


Fig. 4. A comparison of CHF enhancements of pure water on a nanoparticle-coated heater and nano-fluids on a bare heater: (a) TiO₂ nanoparticle with NiCr wire; (b) Al₂O₃ nanoparticle with NiCr wire; (c) TiO₂ nanoparticle with Ti wire.

3.2. Pool boiling CHF experiment of pure water on nanoparticle-coated heater

SEM observation of heater surface subsequent to boiling experiment of nano-fluids revealed that the deposition of nanoparticles on the heating surface occurred during pool boiling of nano-fluids. To independently examine the role of the deposition on CHF enhancement, the pool boiling CHF experiment of pure water was carried out using nanoparticle-coated heater, prepared by the same procedure as pool boiling CHF experiment of nano-fluids. In addition to the experiment of pure water on the nanoparticle-coated heater, an additional pool boiling CHF experiment was carried out when the water used in experiment of pure water on nanoparticle-coated heater was left as it was and only the coated heater was replaced by a bare heater. All values of the supplementary experiments were same as CHF values of pure water on a bare heater within scattering of data. The results indicated that the detachment of nanoparticles from the coated heater was extremely nominal and their effect on CHF was negligible. Therefore, CHF enhancement of pure water on the nanoparticle-coated heater, shown in Fig. 4, is solely attributed to the change of surface characteristics by the nanoparticle coating.

Fig. 4 shows a comparison between CHF enhancements of nano-fluids on the bare heater and pure water on the nanoparticle-coated heater. With no regard to the combinations of nanoparticle and wire, CHF enhancement of pure water on nanoparticle-coated heater was not less high than that of nano-fluids on bare heater for all particle concentrations. Therefore the results clearly show that the nanoparticle surface coating is the main reason for pool boiling CHF enhancement of nano-fluids.

There have been several previous researches on a significant CHF enhancement (~ 3 times) by modifying the heater surface using micron particles [4–6]. And Fukada et al. [7] experimentally studied CHF enhancements of pure water using electrically heated Pt wire (0.03–0.2 mm diameter) fouled through a scale deposition with calcium carbonate. In particular, they emphasized using their experimental data that the slight formation of scale (5–20 μm) fouled on the heater wire could induce the significant increase of about 267% relative to CHF of the bare wire, due to the vigorous detaching behavior of small bubbles from the scale wire of high wettability and high nucleation site density. The nanoparticle surface coating phenomenon during pool boiling using nano-fluids can be regarded as a kind of rapid fouling process, and diameter of the heater wire as well as scale (or coating) thickness were nearly same as the conditions of this study. Accordingly, such significant CHF enhancements of the nanoparticle-coated heater in Fig. 4 are possible enough, and the modification of heater surface resulting from the nanoparticle surface coating can be considered as the main cause of pool boiling CHF enhancement of nano-fluids. Furthermore, the reasons for CHF enhancement of nano-fluids are possibly found from the inspection about the change of heater surface characteristics (such as wettability, surface roughness, and capillary wicking structure), but need further investigation.

In addition, as shown in Fig. 4, CHF enhancements of pure water on the nanoparticle-coated heater exceed CHF enhancement of nano-fluids. This suggests that CHF enhancement obtained by nanoparticle surface coating can be degraded by the interaction of nanoparticles suspended in nano-fluids with the coating structure on wires. Thus, the degrees of the degradations will be differed according to the structure of coating as well as the characteristics of suspended nanoparticles.

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4. Conclusion

The effect of nanoparticles on CHF enhancement in pool boiling of nano-fluids was experimentally investigated. SEM observation of heater surface subsequent to the pool boiling CHF of nano-fluids revealed that a lot of nanoparticles were deposited on heating surface during pool boiling of nano-fluids. CHF enhancements of pure water on the nanoparticle-coated heater were not less high than those of nano-fluids. Conclusively, this study clearly shows that the primary reason of CHF enhancement in pool boiling of nano-fluids is the change of surface microstructure and topography of the heater due to nanoparticle surface coating during pool boiling of nano-fluids.

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