EXPERIMENTAL STUDY ON CHF CHARACTERISTICS OF WATER-TIO2 NANO-FLUIDS

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CHF characteristics of nano-fluids were investigated with different volumetric concentrations of TiO_2 nanoparticles. Pool boiling experiments indicated that the application of nano-fluids, instead of pure water, as a cooling liquid significantly increased the CHF. SEM (scanning electron microscope) observations subsequent to the pool boiling experiments revealed that nanoparticles were coated on the heating surface during pool boiling of nano-fluids. In order to investigate the roles of nanoparticles in CHF enhancement of nano-fluids, pool boiling experiments were performed using (a) a nanoparticle-coated heater, prepared by pool boiling of nano-fluids, immersed in pure water and (b) a nanoparticle-coated heater immersed in nano-fluids. The results demonstrated two different roles of nanoparticles in CHF enhancement using nano-fluids: the effect of nanoparticles coated on the heater surface and the effect of nanoparticles suspended in nano-fluids.

KEYWORDS : CHF, Nano-fluids, Nanoparticle, Surface Coating

1. INTRODUCTION

The enhancement of CHF serves to increase the safety margin of high heat flux thermal systems in nuclear plants such as boiler and coolant systems. Recently, 'nano-fluids', a new kind of heat transfer fluid in which nano-particles are uniformly and stably dispersed, have been considered for the enhancement of pool boiling CHF. You et al. [1] demonstrated that nano-fluids, containing only 0.005 g/l of alumina nanoparticles, yield a dramatic increase (~200%) in CHF in pool boiling at a pressure of 2.89 psia (T_{sat} = 60 ℃). They concluded that the abnormal CHF enhancement of nano-fluids cannot be explained with any existing models of CHF. Vassallo et al. [2] performed experimental studies on pool boiling heat transfer in water-SiO_2 nano-fluids under atmospheric pressure. They showed a remarkable increase in CHF for nano-fluids and also found that stable film boiling at temperatures close to the melting point of the boiling surface is achievable with nano-fluids. Following the experiments, they observed the formation of a thick silica coating on the wire heater. More recently, I.C. Bang et al. [3] showed CHF enhancement in pool boiling on a flat plate heater immersed in water-Al_2O_3 nano-fluids under atmospheric pressure. From the roughness change of the heater surface before and after experiments, they hypothesized that the CHF performance change could be attributed to the nanoparticle surface coating on the heater.

In the present work, in order to investigate the characteristics of CHF enhancement, we performed pool boiling experiments utilizing pure water and nano-fluids with different volumetric concentrations of TiO_2 nanoparticles ranging from 10^{-5} % to 10^{-1} %. In order to assess the deposition of nanoparticles on the heating surface, the heating surface was characterized with scanning electron microscope (SEM) images subsequent to the pool boiling experiment. Then, to estimate the effect of nanoparticles on the CHF of nano-fluids, pool boiling CHF values were measured and compared (a) from a bare heater immersed in nano-fluids, (b) from a nanoparticle-coated heater, which was prepared by deposition of suspended nanoparticles during pool boiling of nano-fluids and immersed in pure water, and (c) from a nanoparticle-coated heater immersed in nano-fluids.

2. EXPERIMENT

2.1. Preparation of Nano-fluids

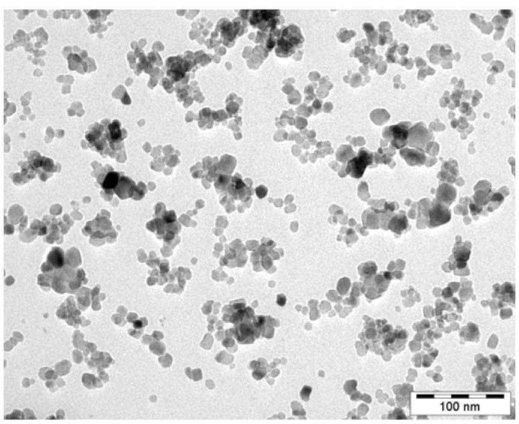
Water-based nano-fluids can vary according to the type of nanoparticles dispersed in the water. In the present

Table 1. Properties of TiO_2 Nanoparticles

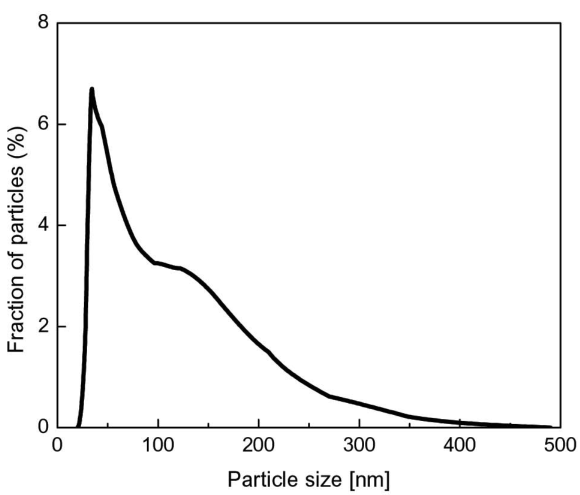
Powder phase	Bulk density (g/liter)	Specific surface area (m^2/g)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)
anatase	4175	56.1	8.4	0.692

Table 2. Major Properties of Prepared Nano-fluids

Nanoparticle	ϕ vol. (%)	k/k_0	μ/μ_0	σ/σ_0
TiO_2	10^{-5}	1.000	1.00	1.00
	10^{-4}	1.000	1.00	1.00
	10^{-3}	1.000	1.01	1.00
	10^{-2}	1.001	1.02	1.00
	10^{-1}	1.003	1.03	1.00



(a)



(b)

Fig. 1. (a) TEM Picture and (b) Size Distribution of TiO_2 Nanoparticles Dispersed in Distilled Water

investigation, TiO_2 nanoparticles, which can be commercially mass-produced, were used to make the nano-fluids. The TiO_2 nanoparticles used in this work were produced using a sol-gel process by Advanced Nano Product Corporation (Korea). Table 1 shows the properties of the TiO_2 nanoparticles.

Solutions with the desired volume concentration of nanoparticles were obtained by mixing the appropriate amounts of distilled water and nanoparticles. For stable dispersion of nanoparticles, ultrasonic excitation during 3 hours was performed. Table 2 shows the properties of the nano-fluids prepared for the experiments. Since the concentrations were dilute, there were no considerable differences in properties for the various concentrations.

Figure 1(a) presents a transmission electron microscope (TEM) image showing the status of TiO_2 nanoparticles dispersed in distilled water. The characteristics of nano-fluids are typically governed by not only the type and size of the nanoparticles but also their dispersion in a base fluid. Individual grains were made having polygonal morphology and a few grains formed into clusters with irregular shapes. The size of nanoparticles dispersed in distilled water ranged widely from 10 nm to 500 nm, as shown in Fig. 1(b), and the mean size was approximately 85 nm.

2.2. Pool Boiling Experiment

A schematic diagram of the experimental apparatus is shown in Fig. 2. The main test pool consists of a 250 mm $\times$ 140 mm $\times$ 250 mm rectangular Pyrex glass vessel and a 30 mm thick Teflon cover. The simple geometry and glass material of the test chamber ensured clean conditions that could be maintained for each experiment. The working fluid was pre-heated using a Corning hot plate and the pool temperature was measured with a Pt-100 ohm RTD

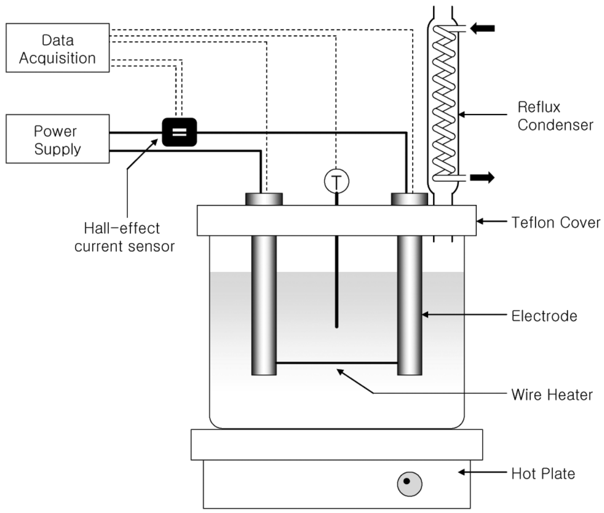


Fig. 2. Schematic Diagram of Experimental Apparatus

sensor. The reflux condenser was mounted on the top cover and cooled with tap water so as to prevent loss of vapor from the test chamber. Accordingly, the volume concentration of the working fluid did not change during the pool boiling. Atmospheric pressure inside the chamber was maintained by the opening on the top of the condenser. A horizontally suspended smooth NiCr wire with 0.2 mm diameter was used as a boiling surface. Both ends of the NiCr wire heater were tightly secured to the clamps of the copper electrodes. The electrodes with 10 mm diameter were connected to a HP agilent 6575A DC power supply (120 V/18 A). A LEM hall-effect current sensor was employed to measure the current and an HP agilent 34970A data acquisition system was used to measure and store voltage, current, and temperature signals.

All pool boiling experiments were conducted after the bulk temperature of the working fluid was stabilized at the saturated temperature (100 ℃). The experiments were performed by increasing the electric power supplied to the wire heater. 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 data obtained just before the steep increase of heater resistance:

$$\dot{q}''_{CHF} = V_{max} I_{max} / \pi D L \tag{1}$$

The experimental uncertainty using the method proposed by Holman [4] is represented as follows:

$$\frac{U_{\dot{q}''_{CHF}}}{\dot{q}''_{CHF}} = \sqrt{\left(\frac{U_{V_{max}}}{V_{max}}\right)^2 + \left(\frac{U_{I_{max}}}{I_{max}}\right)^2 + \left(\frac{U_D}{D}\right)^2 + \left(\frac{U_L}{L}\right)^2} \tag{2}$$

The main sources of uncertainty are the applied voltage and the length of the wire heater. There is contact resistance between the wire heater and copper electrodes, because they are connected with only mechanical clamps. In addition, there is uncertainty associated with the length of the wire heater. The uncertainties of the applied voltage and the length of wire heater are less than 4.0% and 1.7%, respectively. From the above analysis, the maximum uncertainty for pool boiling CHF was estimated to be 4.4%.

3. RESULTS AND DISCUSSION

3.1. CHF of Nano-fluids

The results from pool boiling CHF experiments of distilled water are shown in Fig. 3. The data are scattered within the experimental uncertainty and the mean is appro-

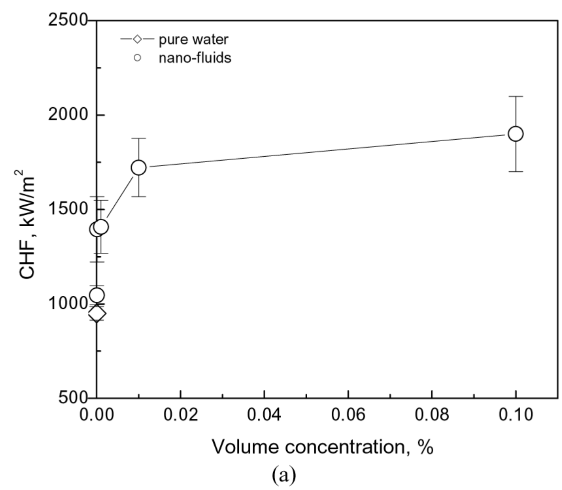


Fig. 3. CHF of Nano-fluids with Different Particle Concentrations Plotted (a) in Linear Scale and (b) in Logarithmic Scale

ximately 25% lower than Zuber [5]'s prediction, which has been widely used to predict pool boiling CHF:

$$\dot{q}''_{CHF,Z} = \frac{\pi}{24}\rho_g^{1/4} h_{fg} \sqrt[4]{g\sigma(\rho_f - \rho_g)} \qquad (3)$$

It was reported by N. Barkhru and J. H. Lienhard [6] that the prediction by equation (3) is not valid and experimental data of previous studies have a large deviation for a sufficiently small horizontal wire such as the 0.2 mm NiCr wire used in this experiment. Since the main focus of the present work is to investigate CHF enhancement using nano-fluids relative to CHF of pure water, the experimental CHF value of pure water in present work can be used as a standard for subsequent CHF comparisons of nano-fluids.

Figure 3 shows pool boiling CHFs of water-TiO_2 nano-fluids with different particle volume concentrations at atmospheric pressure. For nano-fluids with a minimum concentration of 10^{-5}% used for the pool boiling experiment, the CHF was enhanced by only 10% of the value of pure water. However, as the particle concentration increases, the CHF sharply increases up to 160% of the value of pure water at particle concentrations below 10^{-2}%, and then becomes saturated at about 200% at 10^{-1}%. Similar saturation phenomena were reported by You et al. [1] from the results of pool boiling CHF experiments of water-Al_2O_3 nano-fluids under reduced pressure (P_{sat} = 2.89 psia).

For a comparison of the present results with data from previous research, CHF values in nano-fluids normalized

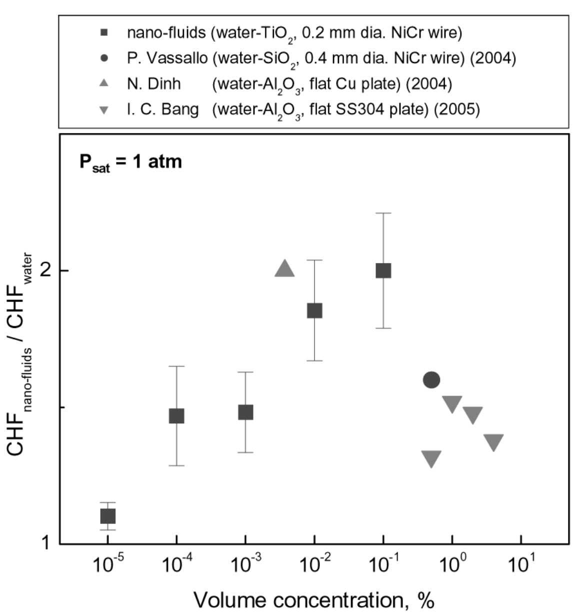


Fig. 4. A Comparison of CHF Enhancements with Previous Experimental Results

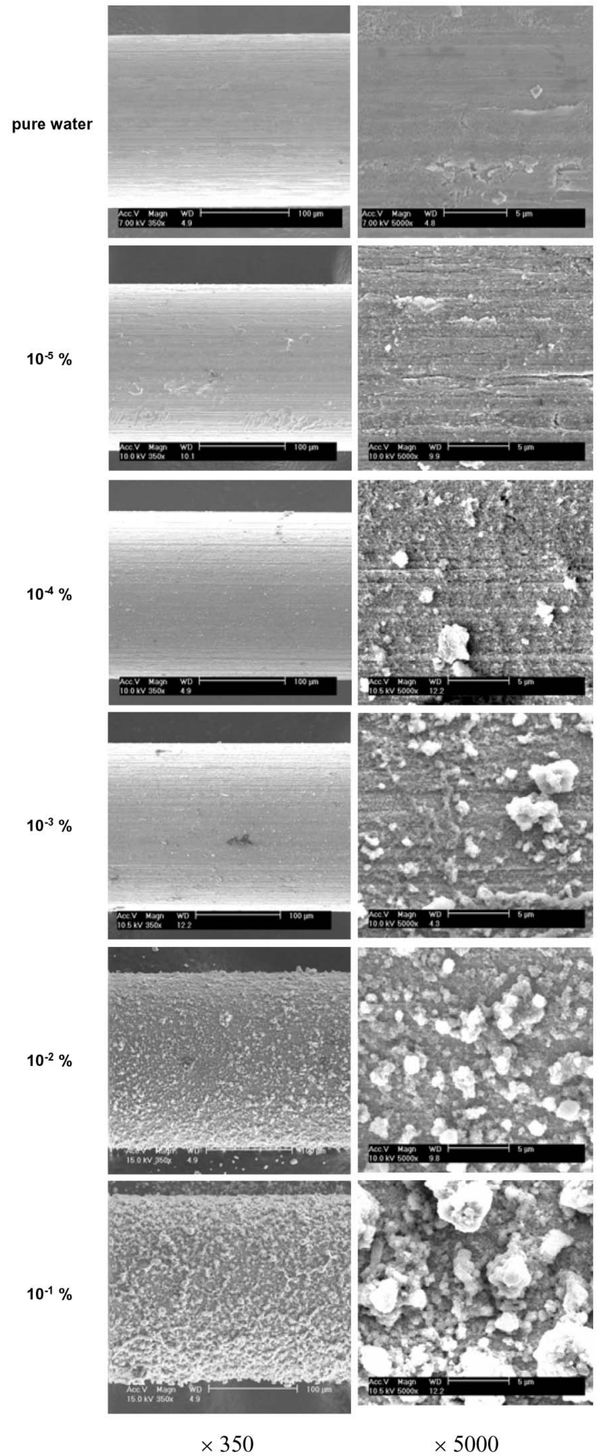
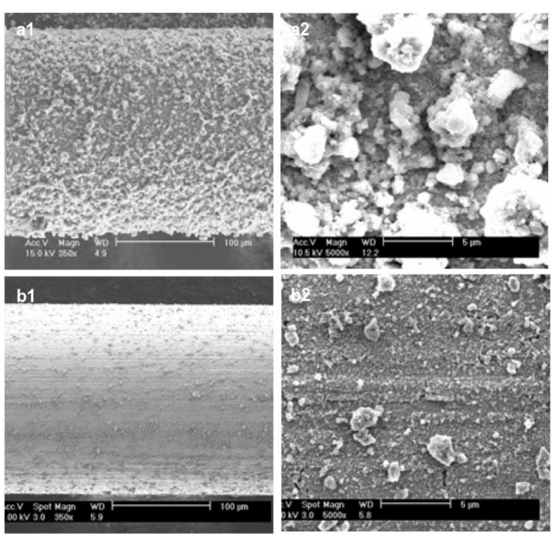


Fig. 5. SEM Picture of Heater Surface After Pool Boiling CHF Experiment in Pure Water and Nano-fluids with Different Particle Volume Concentrations

by CHF of pure water in each work are shown in Fig. 4. Significant CHF enhancement is observed in all works, but there are quantitative differences due to the variation of experimental parameters, such as the material and dispersion conditions of the nanoparticles, as well as the heater geometry, all of which can affect the CHF. In Fig. 5, even for the same nanoparticle material and similar heater geometry (i.e. water-Al_2O_3 nano-fluids on a flat plate heater), roughly 50% difference is observed. In this regard, about 40% difference of CHF enhancement using nano-fluids is possible for the different nanoparticle materials on similar heater geometry (i.e. water-SiO_2 vs. TiO_2 nano-fluids on small horizontal NiCr wire heater). In terms of CHF enhancement by the usage of nano-fluids instead of pure water as a cooling liquid, the results of the present study are consistent with those of other works under atmospheric pressure.

3.2. Coating of Nanoparticles on Heating Surface

Figure 5 shows the characteristics of the heating surfaces after pool boiling CHF experiments of nano-fluids. The microstructure and topography of the heating surface after experiments were changed by the deposition of nanoparticles. During the pool boiling CHF experiment of nano-fluids, immersion of a heating wire only, without heating, also yielded a surface coating of nanoparticles due to the interaction between the surface and nanoparticles. However, it was relatively negligible compared to the coating on the boiling surface, as shown in Fig 6. Moreover, it was impossible to discern the differences between the upside and downside of the heating wire in the pool in terms of the deposition of nanoparticles. In these regards, the formation of nanoparticle surface coatings shown in Fig. 5 can be mainly attributed to the nucleation of vapor bubbles on the cylindrical heating surface, not to the particle-surface interaction in the single phase or directional sedimentation of nanoparticles.



× 350 × 5000

Fig. 6. SEM Picture of the Surfaces After Pool Boiling CHF of 10^{-1} % Nano-fluids; (a) with Heating and (b) Without Heating (Only Immersion)

Modification of the heater surface by the nanoparticle surface coating was dependent on the particle concentration of the nano-fluids. In the case of nano-fluids with the lowest particle concentration, 10^{-5} %, the heating surface displayed only a nominal change. However, as the concentration increased, surface deposition of the nanoparticles thickened and more micro-sized structures were formed on the heating surface.

There have been many previous studies on the effects of heating surface conditions on pool boiling CHF. For example, J. M. Ramilison [7], considering the influence of surface factors such as roughness and contact angle on CHF, suggested the following correlation:

$$\dot{q}''_{CHF} \Big/ \dot{q}''_{CHF,Z} = A\left(\pi - \beta_r\right)^B \left(r\right)^{\left(C+D\beta_r\right)} \tag{4}$$

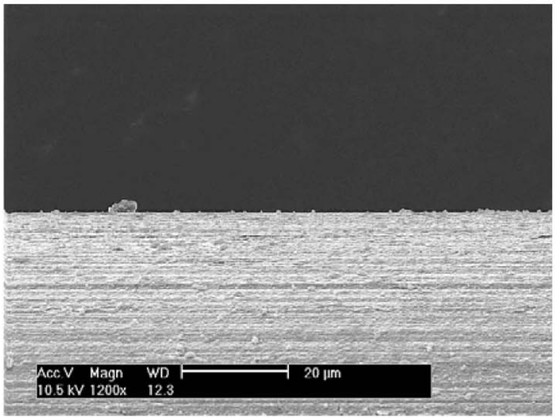
where β_r is the receding contact angle and r is the rms value of surface roughness. His correlation could more accurately predict experimental CHF data found in the literature than Zuber [5]'s. The CHF obtained using Ramilison's correlation is positively proportional to the surface roughness. Furthermore, the surface morphology with micron-scale curvatures presented in Fig. 7(b) can result in capillary wicking, which is well known and used in various two-phase cooling systems such as heat pipes [8]. In addition, the liquid suction effect due to capillary wicking helps supply bulk liquid, and thus boiling crises can be more effectively delayed [9].

Accordingly, it is expected that heating surface enhancement by nanoparticle coating, as shown in Fig. 5, can induce a higher CHF. However, quantitative characterization of the heating surface is necessary in order to elucidate the mechanism of CHF enhancement on the surface. Therefore, surface characterization will soon be carried out using other parameters closely related with boiling: contact angle, surface roughness, and capillary wicking height. In our following paper, the relation of CHF enhancement and the change of heater surface in pool boiling CHF of nano-fluids will be discussed at length.

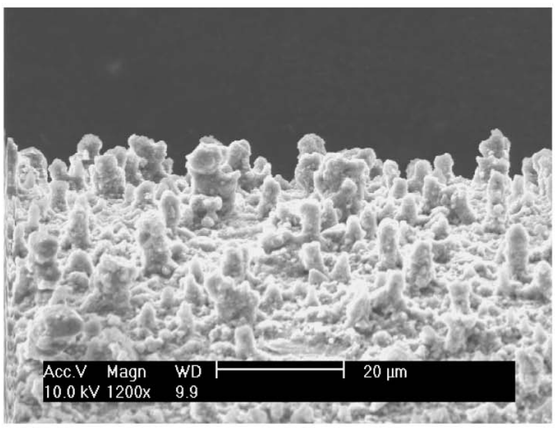
3.3. Effect of Nanoparticles on CHF

Considering the coating of nanoparticles on the heating surface, the effects of nanoparticles on CHF enhancement in nano-fluids can be divided into two groups as follows:

- effect of nanoparticles coated on heating surface
- effect of nanoparticles suspended in nano-fluids



(a) (×1200)



(b) (×1200)

Fig. 7. SEM Picture of Heater Surface after Pool Boiling CHF of Nano-fluids with the Concentration of (a) 10^{-4} % and (b) 10^{-1} % (Side View)

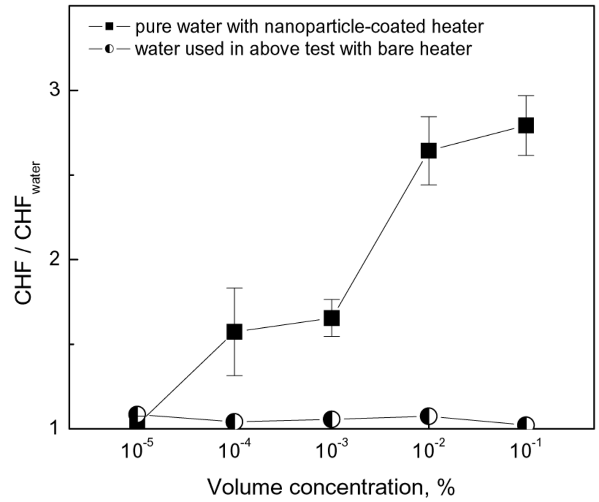


Fig. 8. CHF Enhancement by Nanoparticle Surface Coating

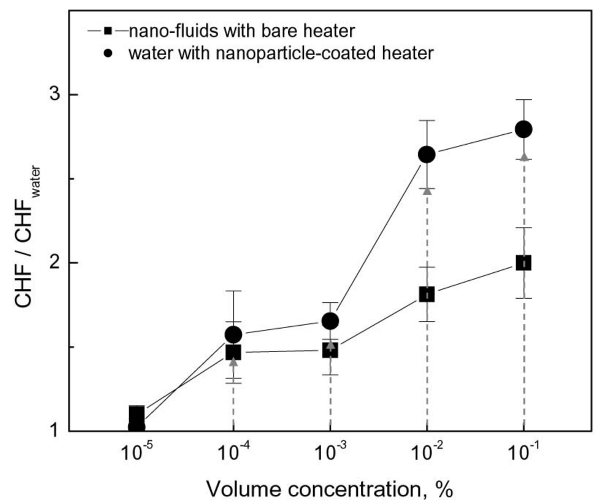


Fig. 9. A Comparison of CHF Enhancements of Pure Water on a Nanoparticle-coated Heater and Nano-fluids on a Bare Heater

Figure 8 shows the effect of nanoparticles coated on the heating surface. The CHF of pure water on the nanoparticle-coated heater varied with the concentration of nano-fluids used for the surface coating. On the other hand, the CHFs on the bare heater immersed in the previously used water for the nanoparticle-coated wire experiment* were nearly constant and the value corresponded with that of pure water on the bare wire within the uncertainty. This indicates that the amount of nanoparticles detached from the nanoparticle-coated surface during pool boiling is extremely small and their effect on CHF is negligible. Therefore, CHF enhancement of pure water on the nanoparticle-coated heater, shown in Fig. 8, can be solely attributed to the change of surface characteristics by the nanoparticle coating. Fig. 9 shows a comparison of CHF enhancement of pure water on the nanoparticle-coated heater with CHF enhancement of nano-fluids on the bare heater. For all particle concentrations, CHF enhancement using nano-fluids is sufficiently achieved by that of pure water on the nanoparticle-coated heater. In this regard, the change of surface characteristics

* This experiment was performed to assess the effect of nanoparticles detached from the nanoparticle-coated surface during pool boiling on CHF. In order to do this, the water used in the previous nanoparticle-coated heater experiment was left as it was and the nanoparticle-coated heater was replaced with a fresh, bare heater.

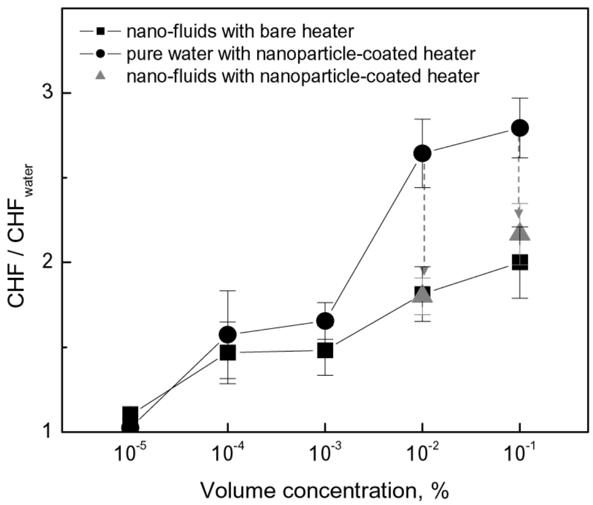


Fig. 10. A comparison of CHF Enhancements of Pure Water on a Nanoparticle-coated Heater, Nano-fluids on a Bare Heater, and Nano-fluids on a Nanoparticle-coated Heater

resulting from the nanoparticle surface coating can be considered as the main cause of pool boiling CHF enhancement of nano-fluids.

Interestingly, at high particle concentrations of 10^{-2}% and 10^{-1}%, in Fig. 8, CHF enhancement of pure water on the nanoparticle-coated heater largely exceeded the enhancement from nano-fluids. Fig. 10 shows a comparison between the CHF of pure water and that of nano-fluids for the nanoparticle coated heaters. CHF enhancement from the nanoparticle-coated heater immersed in pure water is degraded by the replacement of working fluids with nano-fluids, and the value corresponds with the CHF of nano-fluids on the bare heater. Moreover, there are no appreciable differences among heater surfaces after the different pool boiling CHF experiments for each concentration, as shown in Fig. 11. Namely, on the same nanoparticle-coated heater, CHF enhancement from nano-fluids was lower than that from pure water, and the difference is larger in higher particle concentration. The results suggest that nanoparticles suspended in nano-fluids degrade CHF enhancement

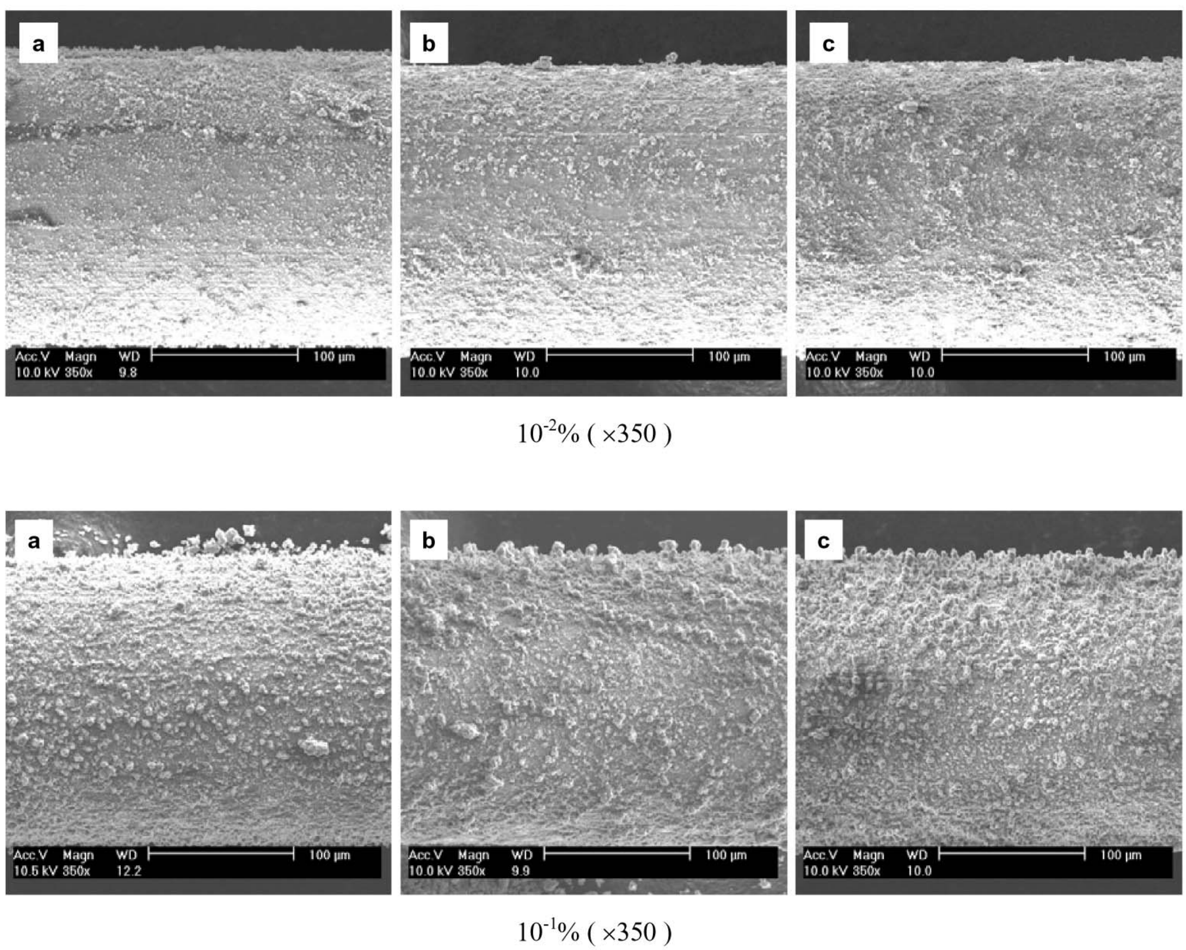


Fig. 11. SEM Picture of Heater Surface after Pool Boiling CHF Experiment of (a) Nano-fluids on a Bare Feater, (b) Pure Water on a Nanoparticle-coated Heater, and (c) Nano-fluids on a Nanoparticle-coated Heater

obtained by nanoparticle surface coating. It is speculated that the nanoparticles suspended in nano-fluids make clogging for the capillary structure, which can give a sufficient liquid supply even at a much higher CHF condition, and resultantly restricts higher enhancement of the CHF. However, the mechanism is still unclear, and more study is needed in this area.

4. CONCLUSIONS

Pool boiling CHF characteristics in nano-fluids were investigated with five volume concentrations of TiO_2 nanoparticles ranging from 10^{-5} % to 10^{-1} %, and the role of nanoparticles in pool boiling CHF of nano-fluids for each concentration was studied experimentally.

Pool boiling CHF of nano-fluids on a bare heater was enhanced to ~200% compared to that of pure water by increasing nanoparticle concentration. SEM images of the heater surface taken after pool boiling CHF tests revealed that CHF enhancement of nano-fluids was closely related to the surface microstructure and enhanced topography resulting from the deposition of nanoparticles. In this regard, pool boiling CHF of water on a nanoparticle-coated heater sufficiently reproduced that of nano-fluids. Moreover, in high nanoparticle concentrations of 10^{-1} % and 10^{-1} %, CHF of pure water on the nanoparticle-coated heater was superior to that of nano-fluids.

This study clearly shows that the main cause of CHF enhancement of nano-fluids is the change of surface microstructure and topography of the heater due to the nanoparticle surface coating formed during pool boiling. It has also been demonstrated that there is another mechanism whereby the application of nano-fluids degrade the CHF enhancement of pure water from the nanoparticle-coated surface.

Acknowledgments

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REFERENCES

[1] S. M. You, J. H. Kim, and K. H. Kim, “Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer,” *Applied Physics Letter*, **83**, 3374 (2003).

[2] P. Vassallo, R. Kumar, and S. D’Amico, “Pool boiling heat transfer experiments in silica-water nano-fluids,” *Int. J. Heat Mass Transfer*, **47**, 407 (2004).

[3] I. C. Bang and S. H. Chang, “Boiling heat transfer performance and phenomena of Al2O3-water nano-fluids from a plain surface in a pool,” *Int. J. Heat Mass Transfer*, **48**, 2407 (2005).

[4] J. P. Holman, Experimental methods for engineers, **7th ed**., Chap. 3, McGraw-Hill, (2001).

[5] N. Zuber, “Hydrodynamic aspects of boiling heat transfer,” AEC Rep. AECU-4439 (1959).

[6] N. Barkhru and J. H. Lienhard, “Boiling from small cylinders,” *Int. J. Heat Mass Transfer*, **15**, 2011 (1972).

[7] J. M. Ramilison, P. Sadasivan, and J. H. Lienhard, “Surface factors influencing burnout on flat heaters,” *J. Heat Transfer*, **114**, 287 (1992).

[8] N. Dinh, J. Tu, and T. Theofanous, “Hydrodynamic and physico-chemical nature of burnout in pool boiling,” *Proc. 5th Int. Conf. on Multiphase Flow*, Yokohama, Japan, 2004.

[9] J. Tehver, “Influence of porous coating on the boiling burnout heat flux,” *Recent Advances in Heat Transfer*, 231 (1992).