©2009 The Visualization Society of Japan
Journal of Visualization, Vol. 12, No. 1 (2009) 37-46

Regular Paper

Wide Range Parametric Study for the Pool Boiling of Nano-fluids with a Circular Plate Heater

Jo, B.*[1], Jeon, P. S.*[2], Yoo, J.*[2] and Kim, H. J.*[3]

*1 Department of Mechanical Engineering, University of Minnesota, 111 Church Street SE, Minneapolis, MN 55455, USA.
*2 Division of Mechanical Engineering, Ajou University, Wonchon-Dong, Suwon, 443-749, Korea.
*3 Division of Mechanical Engineering, Ajou University, Wonchon-Dong, Suwon, 443-749, Korea. E-mail: hyunkim@ajou.ac.kr

Received 12 November 2007
Revised 11 August 2008

Abstract : The characteristics of boiling and critical heat flux (CHF) behavior of nano-fluids with alumina and silver nano-particles suspended in de-ionized water (pure water) were studied with circular plate heaters in the present study. Enhancements of CHF in nano-fluids in the wide range of particle sizes and concentrations were compared with those in pure water. Also, the effects of the particle deposition on CHF enhancement were investigated. All experiments were performed at the atmospheric pressure condition. The results show that the measured boiling curves in nano-fluids were shifted to the right and CHF were significantly enhanced for different nano-particle sizes and concentrations. The CHF of nano-fluids was increased as the size of the nano-particles decreased. On the other hand, nano-particle concentration value showing the maximum CHF had a critical value. In each pool boiling experiment of nano-fluids, nano-particles were deposited on the heater surface. Assuming that this phenomenon caused the CHF enhancement, pool boiling experiments of pure water were carried out with these nano-particle deposited heaters. The results of these tests were similar to those of the test of the nano-fluids for the CHF enhancement. The main cause of CHF enhancement was found to be the change of the heater surface structure. In order to analyze boiling phenomena of pure water and Al_2O_3 nano-fluids, boiling process was visualized by using a high speed camera.

Keywords : CHF, Nano-particle deposition, Superheat, Nano-fluids, Pool boiling

1. Introduction

As semi-conductors have become highly integrated, the cooling of electric devices has been studied. In fields that require a lot of heat dissipation, the heat transfer by phase change is especially important. Studies on the increased conductivities and the heat flux of fluids have introduced nano-fluids, which are pure fluids dispersed with nano particles, and have shown that these nano-fluides have higher conductivity than pure fluid (Choi, 1995). More recently, considerable enhancement of CHF of nano-fluids was achieved by pool boiling of nano-fluids.

You et al. (2003) showed that CHF of alumina nano-fluids in pool boiling with a square plate heater is enhanced by about 200% in the 2.89 psia pressure condition, even when a very small amount of nano-particles is mixed in water (0.01 g/liter). Also, similar results were obtained in pool boiling experiments of water-SiO_2 nano-fluids by using a Ni-Cr wire in atmospheric pressure (Vassallo et al., 2004). Bang et al. (2005) performed the pool boiling of water-Al_2O_3 nano-fluids using a strip shaped plate heater at atmospheric pressure and showed that the roughness of the heater was changed by nano-particle deposition. And they concluded that the deposition might have affected the increase of CHF. Most recently, pool boiling using commercial Ni-Cr wire was performed in an atmospheric pressure condition. The nano-particle coating was shown by SEM (scanning electron microscope) observations. In addition, Kim et al. (2006) and Kim et al. (2007) reported that the CHF of pure water, using the heater coated by nano-particles through pool boiling of nano-fluids was more enhanced than that of nano-fluids. They also showed the differences of the capillary wicking height and contact angle between a bare heater and a coated heater. They believed that these changes in the surface of the heaters enhanced the CHF.

However, previous reports have given results that were obtained from experiments for different conditions. And even though the CHF of nano-fluids showed different values according to the variations of particle size and concentration, detailed parametric studies on the effects of nano-particle size and concentration on CHF enhancement have not been sufficiently established, especially for the plate heater. Since plate-shaped heaters are usually applied in industrial applications, it is important to investigate these types of heaters, comprehensively. In the present study, therefore, we performed pool boiling experiments by using a circular plate heater in the atmospheric pressure condition for a wide range of nano-particles sizes and concentrations. First, to examine the effect of particle size on CHF enhancement, pool boiling experiments of silver nano-fluids of 0.01 g/liter were performed for five different nano-fluids with particle size ranging from 3nm to 250nm. Additionally, pool boiling tests of water-Al_2O_3 nano-fluids were conducted to investigate the boiling characteristics and CHF enhancement at five different concentrations from 10^{-4} to 0.5 g/liter. To investigate the effect of coating on the enhancement of CHF, pool boiling of pure water was carried out using the coated heater obtained through an experiment of nano-fluids, and the CHF values between nano-fluids with a smooth heater and pure water with the coated heater were compared. Simultaneously, the boiling process was visualized by a high speed CCD camera (Kang et al., 2008, Zhang et al., 2008).

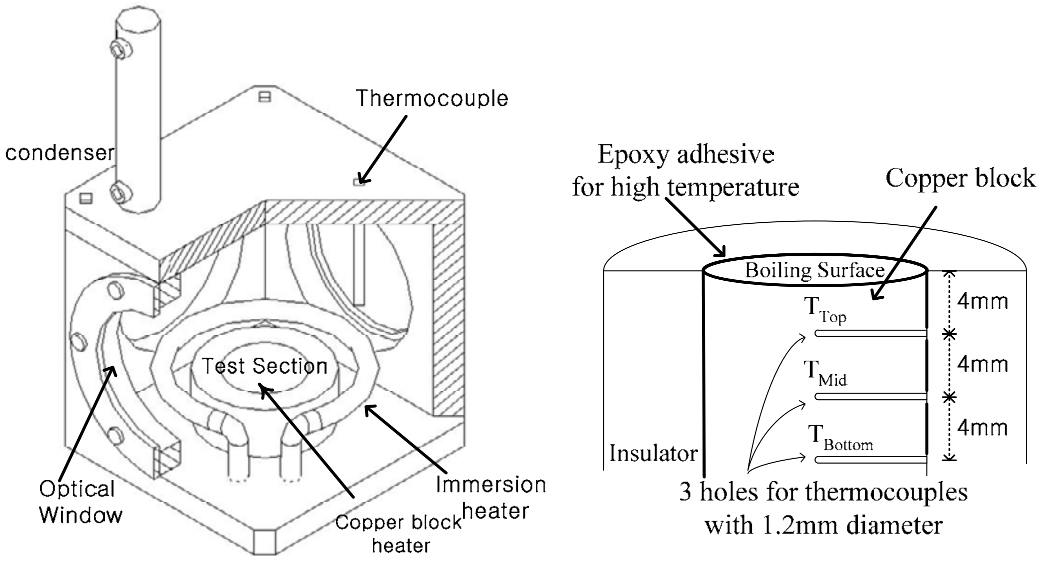
2. Experiment

2.1 Nano-fluids

Two kinds of nano-fluids were used in the experiments. To investigate the effect of particle size on CHF enhancement, five different sizes of silver nano-particle were decided. All particles were mass-produced by several companies, and they were mixed with pure water to obtain a certain mixture concentration. The particle sizes in each water-silver nano-fluid are shown in Table 1, and the fluid concentration was fixed as 0.01 g/liter. For water-Al_2O_3 nano-fluids, the dispersion of the aluminum oxide (Al_2O_3) nano-particles in water, which were also mass-produced by Sigma Aldrich Corporation, was used to study the concentration effect. These fluids had 5 wt % concentration and the particle size was below 25nm. The specification is shown in Table 1. As we did similarly to the silver nano-fluids, we mixed the Al_2O_3 dispersion and pure water to prepare five kinds of nano-fluids of different concentrations. In the experiments with heaters of 15mm diameter, the concentrations of Al_2O_3 nano-fluids varied from 10^{-4} g/liter to 0.5 g/liter. Also, experiments with heaters of 10mm diameter were conducted for three concentrations, 10^{-3} g/liter, 10^{-2} g/liter, and 10^{-1} g/liter, to confirm the trend of the concentration effect.

Table 1. Nano-particle sizes and concentrations of nano-fluids

Materials (Density)	Particle size (nm)	Concentration (g/liter)	Materials (Density)	Particle size (nm)	Concentration (g/liter)
Silver (1.05 g/cm^3)	3	0.01	Al_2O_3 (1.08 g/cm^3)	< 25	10^{-4}
	10				10^{-3}
	80				10^{-2}
	150				10^{-1}
	250				0.5



(a) Schematic of boiling chamber (b) Schematic of copper block heater assembly

Fig. 1. Schematics of experimental apparatus.

2.2 Experimental apparatus

Figure 1(a) shows the schematic of the boiling apparatus. The chamber of about 2 liter volume was made of aluminum. And an immersed pipe heater of 1.5kW degases pure water before the pool boiling and maintains the temperature of the pool during an experiment. Through the cover of the chamber, a K type sheathed thermocouple is inserted to measure the temperature of the pool. And an external condenser is also mounted at the cover to return the evaporated fluid and then to maintain the concentration of nano-fluids constantly.

Actually, pool boiling was initiated from the surface of the cooper block heater assembly. It consists of three parts: cartridge heaters, a circular cooper block, and an insulator, as shown in Fig. 1 (b). Three cartridge heaters are inserted into the lower part of the copper block, and the thermal energy from the heaters is conducted to the boiling surface. To estimate the superheat of the boiling surface and the heat flux, three holes were pierced in the upper part of the copper block at equal distances, and three K-type thermocouples are adhered into these holes with high conductivity thermal resins, which reduces the contact resistances. And these thermocouples were connected to the Yokogawa DA-100 Data Acquisition System. To simplify the heat transfer as one-dimensional conduction, the cooper block is surrounded with an PEEK insulator, whose conductivity is about 1000 times lower than that of copper.

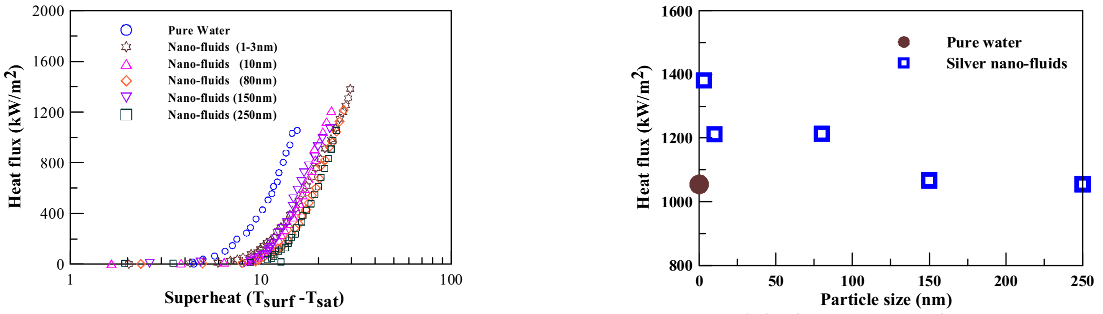
2.3 Experiment procedures

As the first step, pool boiling of pure water was carried out to verify the thermal reliability of the test facility, comparing the measured CHF with the prediced value (Zuber, 1959). After verification of the boiling system, experiments of each nano-fluid in Table 1 were carried out. Before the pool boiling experiment, a degassing process by the immersed pipe heater was carried out to remove the remaining gas in the pool thoroughly. During the experiment, electric power was supplied to the cartridge heaters via the AC transformer, and it was continuously monitored and maintained constant at each voltage step. At each voltage level, steady state temperature for T_{Top}, T_{Mid} and T_{Bottom} was identified within below 0.2℃ standard deviation, and then the power supplied to the cartridge heater was increased to the next level. The temperature data from the cooper block were monitored and stored continuously. Based on the measured data, surface temperatures and heat fluxes were calculated by Equations (1) and (2). T_{surf} in Eq. (1) is the temperature of the boiling surface in the cooper block heater in Fig. 1 (b). T_{Top} and T_{Bottom} are the measured temperatures at the nearest point and the farthest point from a boiling surface, respectively. And d is the distance between each thermocouple in a cooper block.

$$T_{surf} = T_{Top} - \frac{1}{2}\left(T_{Bottom} - T_{Top}\right) \qquad (1)$$

$$q'' = k\left(T_{Bottom} - T_{Top}\right)/2d \qquad (2)$$

To remove the contamination by different nano-particles that remain in the chamber and to set accurate nano-fluids concentrations, the inside of chamber was cleaned thoroughly for every following boiling. To eliminate the influence of surface roughness, the surface of the heater was polished by CC-2000Cw sand paper for all experiments. In addition, the coated heater obtained from the nano-fluids experiments was also used without any surface treatment to investigate the effect of surface roughness on CHF enhancement.



(a) Boiling curves of silver nano-fluids (b) Critical heat flux values

Fig. 2. Boiling curves and CHF values of silver nano-fluids for particle sizes.

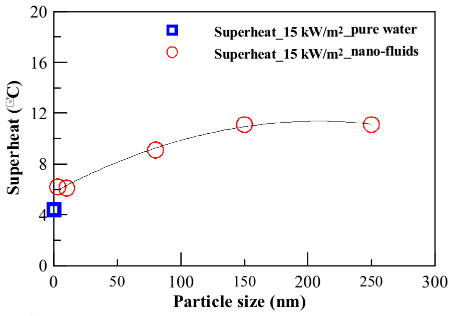


Fig. 3. Superheats as particle variations at a low heat flux.

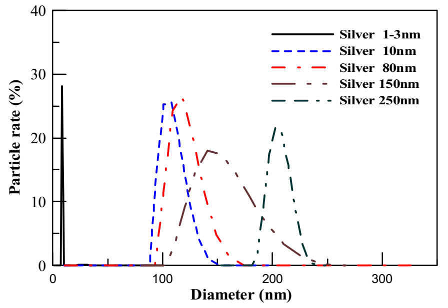


Fig. 4. Particle size distribution of silver nano-fluids.

3. Result and Discussion

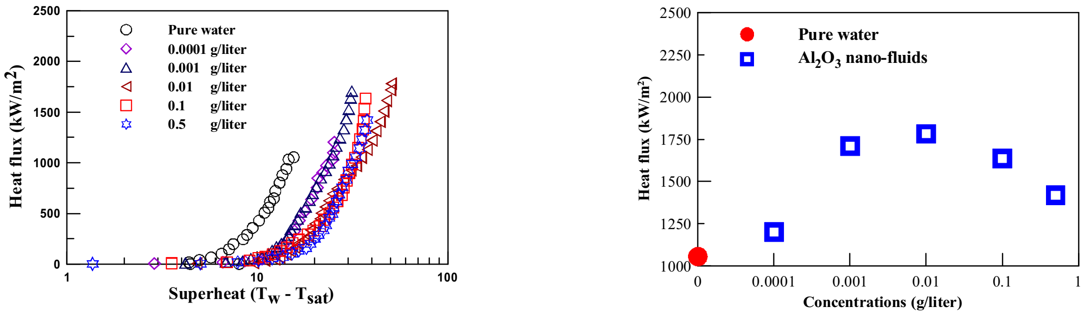
3.1 Particle size effect

Figure 2 shows the results of pool boiling of silver nano-fluids, which was carried out to understand the effect of particle size on CHF enhancement. As shown in Fig. 2 (a), CHF of pure water is about 1055 kW per a square meter, which is in good agreement with the predicted value, 1106kW per a square meter. In Fig. 2 (a), the boiling curves of silver nano-fluids are shifted to the right with respect to that of pure water. This means that the nucleate boiling regime in nano-fluids is delayed in terms of superheat.

The superheats of pure water, in which isolated bubbles start to depart from the heater surface and heat flux is about 15kW per a square meter, was 4.4℃,which is similar to that given by the Nukiyama curve (Incropera and Dewitt, 2003). In the cases of silver nano-fluids, however, the superheats of silver nano-fluids at 15kW/m^2 range from 6.1℃ to 11.1℃ with the variation of particle size. As shown in Fig. 3 from these results, the superheat in silver nano-fluids increases in proportion to the size of the dispersed particle. This increase of the superheat could be due to the fact that the nano-particles in the water reduced the number of active nucleate sites on the heater surface and thus hindered bubble departure from the boiling surface, as suggested in the past study (Li et al., 2003). If a heater surface is treated roughly, nano-particles precipitated from the surface, reducing the nucleate sites on the surface (Das et al., 2003). Consequently, the particles in the water would delay the increase of heat flux.

As shown in Fig. 2(b), the CHF of nano-fluids with 3nm particles show the greatest increase (~31%), and CHF values of 10nm and 80nm are similarly increased by as much as about 15%. On the other hand, where the CHF values are 150nm or 250nm, the increase of CHF is nearly negligible. The above result explains that small particles contributed to CHF enhancement.

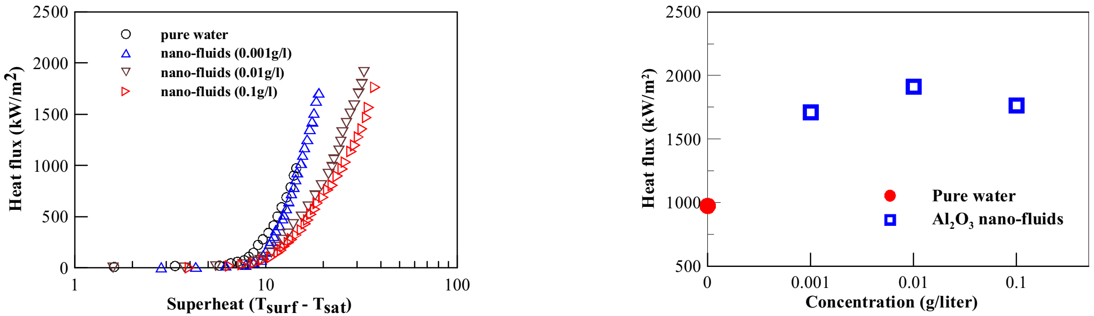
Throughout the experiments on silver nano-fluids, the superheat in the low heat flux regime was shown to increase and the CHF enhancement to decrease as the size of the particles dispersed in water increased. In order to verify this finding, we measured nano-particle sizes by using a particle size analyzer (FPAR-1000, Photal Otsuka Corporation). Figure 4 shows the result, and it fully explains why the CHF for nano-fluids of 10nm particles is similar to that of 80nm particles. In these cases, although the original particle sizes are 10nm and 80nm, respectively, 10nm particles agglomerate in water, so the average size becomes similar. Therefore, it can be concluded that the reduction of nano-particle size in fluids delays nucleate boiling and enhances the CHF.



(a) Boiling curves of Al_2O_3 nano-fluids

(b) Critical heat flux values

Fig. 5. Boiling curves and CHF of Al_2O_3 nano-fluids with 15mm diameter heater.



(a) Boiling curves Al_2O_3 nano-fluids

(b) Critical heat flux values

Fig.6. Boiling curves and CHF of Al_2O_3 nano-fluids with 10mm diameter heater.

3.2 Concentration effect

In order to investigate the effect of concentration on CHF enhancement, pool boiling experiments of Al_2O_3 nano-fluids were performed with two different heaters of 10mm diameter and 15mm diameter. After the pool boiling experiments with 15mm diameter heaters and obtained a trend of the CHF with the variation of concentration, we performed experiments with 10mm diameter heaters for Al_2O_3 nano-fluids. Figure 5 shows the boiling curves and CHF of Al_2O_3 nano-fluids with the 15mm diameter heaters. As shown in Fig. 5 (a), the boiling curves of nano-fluids are shifted to the right as the concentration increases. And CHF is significantly enhanced at all concentrations, compared with pure water, and especially the maximum CHF was achieved at the concentration of 0.01 g/liter.

To verify the trend in Fig. 5, experiments with 10mm diameter heaters were carried out at three different concentrations from 10^{-3} g/liter to 10^{-1} g/liter. The results are shown in Fig. 6. Like the result with the 15mm heater, the boiling curves of nano-fluids are moved to the right, compared with pure water, and the maximum CHF value is also obtained at 0.01 g/liter. From the above result, excessive additions of nano-particles are expected to decrease the CHF in nano-fluids.

CHF increase is considered to be caused by a well-supply of fluids into the surroundings of the departing bubbles near the heater surface. In nano-fluids, namely, grown-up micro-convection contribution affected the rise of heat flux (Kim et al. 2006). Accordingly, micro-convection worked more effectively, and CHF is delayed in pool boiling of nano-fluids, compared with pure water(unclear comparison). At high concentrations, however, particles in water could be the obstacles that reduce micro convection contribution, so CHF was decreased beyond a certain concentration. And CHF for a 10mm diameter heater increased slightly more than 15 mm. The maximum difference of the CHF enhancement ratio was approximately ~27% at 0.01 g/liter and at all concentrations, the CHF for the 10mm heater was higher than that for the 15mm heater. Therefore, the expansions of the heating area are thought to have diminished the CHF enhancement in pool boiling. Apparently, it is caused by the fact that micro convection could have a more dominant effect in small heaters. CHF values and the enhancement ratios of Al_2O_3 nano-fluids are summarized in Table 2. CHF values and the enhancement ratio of Al_2O_3 were higher than the results of silver nano-fluids. According to the results, a lot of heat flux enhancement was obtained at low concentrations below 10^{-2} g/liter (10^{-5} vol%) with just a little temperature rise.

Compared with results by other researchers who performed experiments at atmospheric pressure, the CHF enhancement of the present study was lower than that of pool boiling with a wire heater (~60%, ~100%) (Vassallo et al., 2004 and Kim et al., 2007), but was higher than the results for a plate of 100mm² (~50%) of Bang and Chang (2005) in Fig. 7. Considering the results in the past, there has been no enhancement of CHF above ~ 100% in pool boiling experiments with the plate heater except in experiments at low pressures (You et al., 2003). Only with the wire heater, CHF was enhanced by approximately ~ 100%. Because plate-shaped heaters are usually applied to industrial applications, data in the present study could be considered as practical and indicative of the maximum increase of CHF for flat plate heaters, so far. Figure 7 compares the results of the CHF enhancement ratio from the present study with other results obtained for the atmospheric pressure condition.

Table 2. CHF and CHF enhancement for Al_2O_3 nano-fluids

Materials	Concentration (g/liter)	Heater size : 10mm diameter		Heater size : 15mm diameter	
		CHF (kW/m²)	Enhancement (%)	CHF (kW/m²)	Enhancement (%)
Water	0	973	N/A	1055	N/A
Al_2O_3	0.0001	N/A	N/A	1201	13.8
	0.001	1710	75.7	1709	62.0
	0.01	1911	96.4	1782	68.9
	0.1	1764	81.3	1635	55.0
	0.5	N/A	N/A	1419	34.5

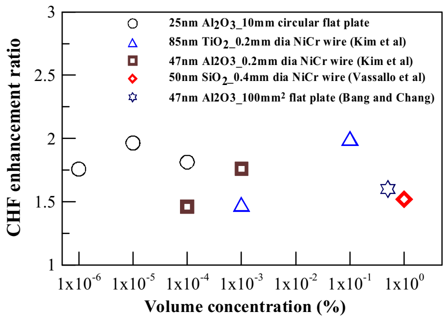
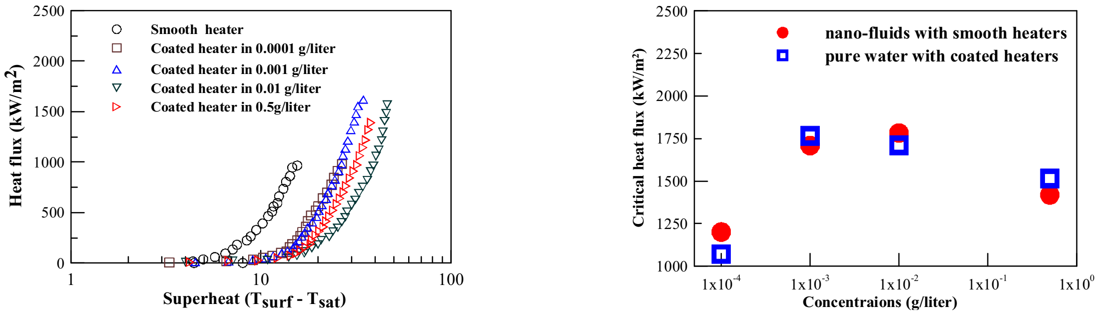
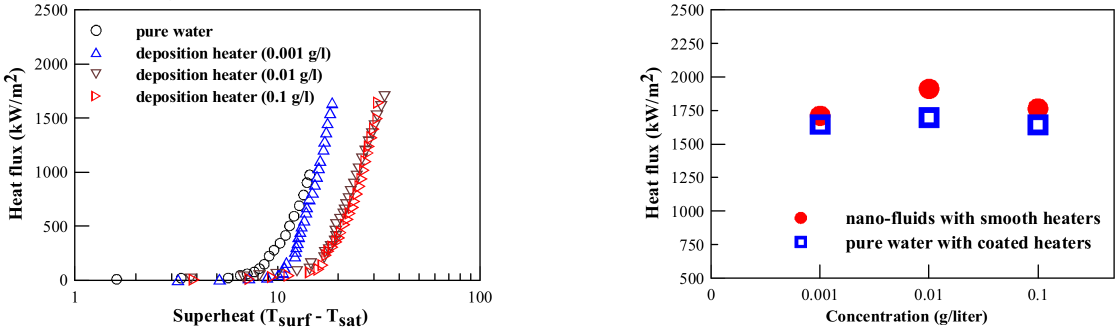


Fig. 7. CHF enhancement ratios of nano-fluids from several studies.



(a) Boiling curves from coated heaters (b) CHF from coated heaters

Fig. 8. Boiling curves and CHF of pure water from Al_2O_3 nano-particle coated 15mm heaters.



(a) Boiling curves from coated heaters (b) CHF from coated heaters

Fig. 9. Boiling curves and CHF of pure water with Al_2O_3 nano-particle coated 10mm heaters.

After pool boiling of Al_2O_3 nano-fluids, special observation was made about the heater surface. Nano-particles were deposited on the surface. Because we believed that this coating could influence the CHF, we carried out the pool boiling of pure water with nano-particles deposited heater.

3.3 Nano-particle coating

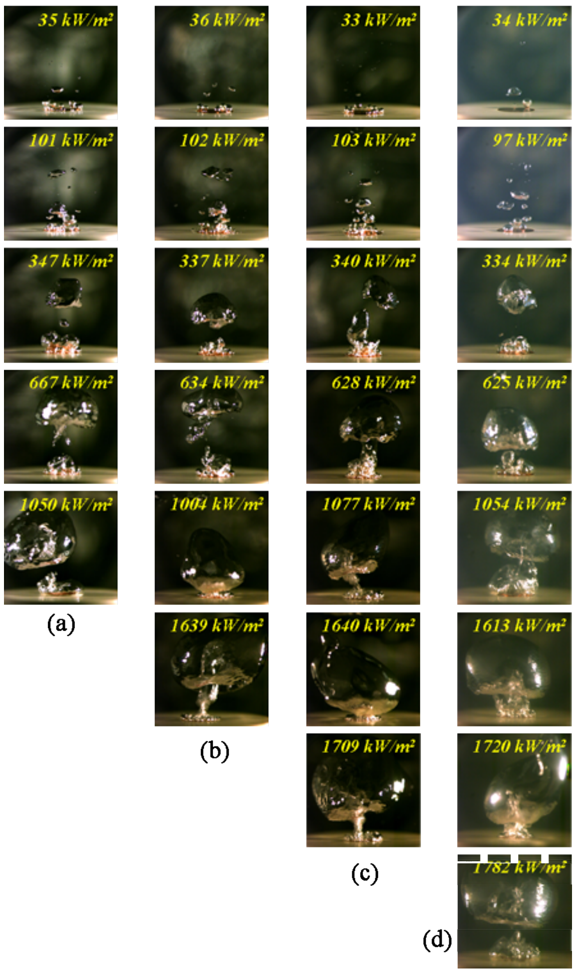
Figure 8 and Fig. 9 show the boiling curves and CHF of pure water for Al_2O_3 nano-particles deposited heaters. Seven different coated heaters, which have been made through experiments in section 3.2, were applied to pure water to investigate the concentration effect of the nano-fluids in 3.2. Though these are the boiling curves of pure water, they are similar to the ones of the nano-fluids, as shown in Fig. 8 (a) and Fig. 9 (a). The shift of the curves to the right and CHF enhancement were observed in all measured curves obtained with the use of coated heaters. As shown in Fig. 8 (b) and in Fig. 9 (b), the CHFs between nano-fluids using smooth heaters and pure water using coated heaters have a little difference of less than about ~11%.

Furthermore, Fig. 8 and Fig. 9 show that the CHF enhancements obtained with use of the coated heaters are similar with those obtained with smooth heaters. That is, the nano-particle coating is expected one of the possible causes contributing to the enhancement of CHF in nano-fluids. Though experiments in the present study were carried out at very low concentrations, the coating was observed by the naked eye after pool boiling of the nano-fluids. Therefore, additional investigation about nano-particle deposition will be needed to determine and understand the causes and mechanism for pool boiling of nano-fluids.

3.4 Visualizations

Boiling procedures with 15mm heaters were visualized in this study. Figure 10 shows and compares the boiling phenomena of pure water and Al_2O_3 nano-fluids of three concentrations at several similar heat fluxes by using a high speed camera (Photron, APX-RS) and a fiber illuminator. All photographs were taken at 1000 fps (frame per second). As shown in Fig. 10, there are no differences between the pictures of pure water and nano-fluids until about 1000 kW/m². At low heat fluxes (about 100kW/m²), small bubbles depart from the boiling surface. As the heat flux increases, small bubbles unite from the surface, grow larger in volume, and leave from the surface. Note that the boiling of pure water reaches the limit at near 1000 kW/m^2 while that of nano-fluids extends to higher heat fluxes. As the heat fluxes of nano-fluids become higher than the CHF of pure water, bigger bubbles than those of water are obtained after the CHF of pure water.

In order to compare boiling phenomena and find discrepancies between smooth heaters and coated heaters, we obtained pictures during pool boiling of nano-fluids with smooth heaters and pure water with coated heaters. Like the photographs in Fig. 10, there are no remarkable differences between the two cases, as shown in Fig. 11. At the low heat fluxes (below 100kW/m^2), however, a difference in the size of bubble from boiling surfaces was found. This difference indicates that the coated surface by Al_2O_3 nano-particles enabled the formation of minute bubbles on the heating surface. However, the estimated CHF of smooth heaters and coated heaters do not have a particular discrepancy, as mentioned earlier. In relation, Fig. 11 shows that bubble shapes for the four cases become similar as the heat flux increases.



(a) (b) (c) (d)

Fig. 10. Visualizations of pure water and Al_2O_3 nano-fluids : (a) pure water, (b) 10^{-4} g/liter, (c) 10^{-3} g/liter, (d) 10^{-2} g/liter.

(a) (b) (c) (d)

Fig. 11. Visualizations of Al_2O_3 nano-fluids with smooth heaters and pure water with coated heaters : (a) Nano-fluids of 10^{-3} g/liter with a smooth heater, (b) pure water with a coated heater of 10^{-3} g/liter, (c) Nano-fluids of 10^{-2} g/liter with a smooth heater, (d) pure water with a coated heater of 10^{-2} g/liter.

4. Conclusion

Boiling characteristics and CHF enhancement according to particle size, heater dimensions, and concentrations were investigated by pool boiling experiments of nano-fluids. Especially, the CHF enhancement was primarily studied through experiments with bare heaters and coated heaters.

(a) CHF is significantly enhanced in nano-fluids. The boiling curves of all nano-fluids are shifted to the right, and they are affected by the particle size from pool boiling of silver nano-fluids.

(b) The result for pool boiling of silver nano-fluids shows that the CHF of fluids in which small particles are dispersed are higher than those in which large nano-fluid particles are dispersed.

(c) CHF is enhanced even at very low concentrations. It is increased as the concentration rises up tp 0.01 g/liter, but after this point, CHF is decreased even as the concentration rises. Also, CHF is also influenced by the heater area.

(d) The coating on the boiling surface has an effect on CHF augmentation. It could be the primary effect on CHF enhancement, as shown by the similar enhancement values between pure water with smooth heaters and nano-fluids with coated heater.

Acknowledgements

This work was supported by the Grant of Korea Science Engineering Foundation (R05-2004-000-11406). Also, the authors gratefully acknowledge financial support from the Micro Thermal System Research Center sponsored by the Korean Science and Engineering Foundation, Korea.

References

Choi, U. S., Enhancing thermal conductivity of fluids with nano-particles, ASME, FED, 231 (1995), 99-105.

You, S. M., Kim, J. H. and Kim, K. H., Effect of nano-particles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett., 83 (2003), 3374-3376.

Vassallo, P., Kumar, R. and D'Amico, S., Pool boiling heat transfer experiments in silica-water nano-fluids, Int. J. Heat Mass Transfer, 47 (2004), 407-411.

Bang, I. C. and Chang, S. H., Boiling heat transfer performance and phenomena of Al2O3-water nano-fluids from a plain surface in a pool, Int. J. Heat Mass Transfer, 47 (2005), 2407-2419.

Kim, H., Kim, J. and Kim, M. H., Effect of nano-particles on CHF enhancement in pool boiling of nano-fluids, Int. J. Heat Mass Transfer, 49 (2006), 5070-5074.

Kim, H., Kim, J. and Kim, M. H., Experimental studies on CHF characteristics of nano-fluids at pool boiling, Int. J. Multiphase Flow, 33 (2007), 691-706.

Kang, J. H. and Lee, S. J, .Mechanical Response of Young Canes of Wind-Blown Kiwifruit Vines, J. Visualization, 11-3 (2008), 231-238.

Zhang, W., Kang, J. H. and Lee, S. J., Visualization of Saltating Sand Particle Movement near a Flat Ground Surface, J. Visualization, 10-1 (2008), 39-46.

Zuber, N., Hydrodynamic aspects of boiling heat transfer, Ph. D. thesis, UCLA, Los Angeles, CA (1959).

Incropera, F. P. and Dewitt, D. P., Fundamentals of Heat and Mass Transfer (Fifth edition), (2003), 666-672, John Wiley and Sons, New York.

Li, C. H., Wang. B. X. and Peng., X. F., Experimental investigation on boiling of nano-particle suspensions, Boiling Heat Transfer Conference, (Jamaica), (2003).

Das, S. K., Putra, N. and Roetzel, W., Pool boiling characteristics of nano-fluids, Int. J. Heat Mass Transfer, 46 (2003), 851-861.

Kim. J. H., You, S. M. and Pak, J. Y., Effects of heater size and working fluids on nucleate boiling heat transfer, Int. J. Heat Mass Transfer, 49 (2006), 122-131.

Author Profile

Byeongnam Jo: He received his B.S. and M.S. (Eng) degree in Mechanical Engineering in 2007 from Ajou University. He worked at the National Research Laboratory as a research assistant for his master course at Ajou University. He performed several researches related to measurement of thermal properties, visualization, and boiling heat transfer. He has studied and worked at University of Minnesota since fall 2007. His research interests are bio-preservation, bio-heat transfer and visualization.

Pilsoo Jeon: He received his B.S. degree in Mechanical Engineering in 1998 from Kongju National University. He received his M.S. and Ph.D. degree in Mechanical Engineering in 2007 from Ajou University. He currently works in Thermofluid Systems Control Laboratory as a researcher at Ajou University. His research interests are thermophysical property measurement and electric device cooling.

Jaisuk Yoo: He received his B.S. and M.S. degree in Mechanical Engineering in 1980 from Seoul National University. He received his Ph.D. in Mechanical Engineering in 1984 from University of California, Berkeley. He currently works in Division of Mechanical Engineering, Ajou University as a professor since 1985. His research interests are nano fluidics, micro scale heat transfer and optical property measurement.

Hyun Jung Kim: He received his B.S. and M.S. degree in Mechanical Engineering in 1996 from Hanyang University. He received his Ph.D. in Mechanical Engineering in 2001 from Texas A&M University. He currently works in Division of Mechanical Engineering, Ajou University as an associate professor since 2003. His research interests are nano fluidics, optical property measurement, micro scale heat and mass transfer and measurement with Micro PIV, LIF.