

EFFECT OF SOLUBLE ADDITIVES, BORIC ACID (H_3BO_3) AND SALT (NaCl), IN POOL BOILING HEAT TRANSFER

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The effects on pool boiling heat transfer of aqueous solutions of boric acid (H_3BO_3) and sodium chloride (NaCl) as working fluids have been studied. Borated and NaCl water were prepared by dissolving 0.5~5% volume concentration of boric acid and NaCl in distilled-deionized water. The pool boiling tests were conducted using $1 \times 1 \text{ cm}^2$ flat heaters at 1 atm. The critical heat flux (CHF) dramatically increased compared to boiling pure water. At the end of boiling tests it was observed that particles of boric acid and NaCl had deposited and formed a coating on the heater surface. The CHF enhancement and surface modification during boiling tests were very similar to those obtained from boiling with nanofluids. Additional experiments were carried out to investigate the reliability of the additives deposition in pure water. The boric acid and NaCl coatings disappeared after repeated boiling tests on the same surface due to the soluble nature of the coatings, thus CHF enhancement no longer existed. These results demonstrate that not only insoluble nanoparticles but also soluble salts can be deposited during boiling process and the deposited layer is solely responsible for significant CHF enhancement.

KEYWORDS : Pool Boiling, Nanocoating, Critical Heat Flux, Soluble Additive

1. INTRODUCTION

Critical heat flux (CHF) is known to be a limiting factor for heat dissipation in two-phase boiling heat transfer (BHT). When the CHF is reached, the vapor forming at the surface of the heater envelops the entire surface of the heater. This blanketing of the surface causes the temperature of the surface to drastically increase, resulting in system failure. Over a decade, delaying the occurrence of CHF, which is one of the critical phenomena of boiling, has been extensively researched. In the recent past, nanofluids, consisting of nano-sized particles dispersed in a liquid, have shown great potential due to their ability to reach higher CHF than water or most of the other liquids.

Yang and Maa [1] were among the first researchers to investigate the effect of nanofluids in pool boiling heat transfer. About two decades later, extended studies of their performance in pool boiling were resumed by Das et al. [2], You et al. [3], and Vassallo et al. [4]. Particularly, nanofluids were highlighted after You et al. [3] and Vassallo et al. [4] showed a dramatic CHF enhancement by ~200% and ~60% using alumina (Al_2O_3)-water nanofluids and silica (SiO_2)-water nanofluids, respectively. Since these initial findings, later studies [5-10] confirmed this CHF

enhancement to various degrees using various nanofluids and heater geometries.

Although CHF almost always increased relative to the value attained with the pure fluid, there were contradictory results on BHT performance. Some researchers reported that nanofluids enhanced BHT [1, 11, 12]. While others such as Das et al. [2] and Bang and Chang [6] found them to decrease BHT, and some studies [3, 4, 9] found them to have no effect or to degrade BHT. Das et al. [14] looked into the effects of surface roughness, particle size and nanoparticle concentration. Even though in some studies different surface characteristics were reported, i.e., smoother [2] and rougher [6], the consensus on BHT degradation was that it was caused by the nanoparticle deposition on the heater surface during boiling. This nanoparticle deposition reduced or increased the active nucleation site density, depending on whether the deposition decreased or reduced the roughness. Also, the deposition, if sufficiently thick, resulted in increase of thermal resistance.

Then, researchers [9, 10, 13, 14] made an effort to determine the mechanism of CHF enhancement. Sefiane [13] showed that CHF enhancement was related to structural disjoining pressure and contact angle pinning. Kim et al.

[9] revealed a positive relationship between the CHF value and the wettability of the heater surface. Kim and Kim [10] confirmed that the nanoparticle deposition or coating alone was indeed the source of CHF enhancement.

Most recently, Kwark et al. [15] showed that nanofluid boiling is transient due to the dynamic nature of the coating formation process and confirmed that the microlayer evaporation, proposed by Kim et al. [9], was the major mechanism of nanoparticle deposition. Furthermore, Kwark et al. [16] reported a linear relationship between CHF enhancement and the quasi-static contact angles on the nanoparticle coatings or nanocoatings, confirming a strong CHF dependence on surface wettability. Additionally, they measured the speed of the liquid meniscus during vertical dipping tests and found it to be on the order of the superficial vapor velocity. They indicated that the speed of the liquid front, advancing in on the growing and departing bubbles, may be fast enough to keep the heater surface wet. Therefore, they attributed the speed of the thin liquid wetting front advancing in underneath of the growing bubble, to be the main reason for the dramatic CHF enhancement of nanocoatings.

Since it had become clear that not the enhanced thermophysical properties, but the surface modification alone is the source of nanofluid boiling enhancement, the attention shifted from nanofluids in pool boiling to the nanoparticle coating formed on the heated surfaces during nanofluid boiling. By different methodologies, Kwark et al. [17] and Forrest et al. [18] successfully generated nanoparticle coated heaters which maximized the CHF while not degrading the BHT. Kwark et al. [17] developed the coating by the boiling process (micro evaporation process). On the other hand, Forrest et al. [18] produced their nanoparticle coating independently of pool boiling. These results showed that the usefulness of nanofluids is in the byproduct of boiling (e.g. nanoparticle coating), not necessarily in the nanofluid itself.

In the present paper, instead of using nanofluids, borated and NaCl water were used as working fluids and their effects on the boiling heat transfer were studied. These two solutions are chosen in this study because they have been used as heat transfer media in PWR (pressurized water reactor) systems and in desalination processes. However, to the authors' knowledge, few reports regarding the pool boiling of borated water and NaCl water are available.

Unlike nanofluids, borated and NaCl water are single phase (e.g. additives are completely dissolved into water). As supporting our previous argument of the significance of nanoparticle coating for CHF enhancement [16], the results showed that these single phase solutions provided dramatic increase of CHF compared to pure water due to surface coating built up during boiling. It was observed after the boiling experiments that boric acid and NaCl particles had been deposited on the heater surface.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Test Vessel

A schematic of the pool boiling test vessel is shown in Fig. 1 (a). The test vessel has two reinforced glass windows on the front and back as view ports. The dimensions of the apparatus are 20 cm (wide) \times 20 cm (high) \times 17 cm (depth). Two half-inch diameter (1000 W) cartridge heaters were mounted in the vessel for rapid heating and degassing. Band heaters were externally attached to the test vessel to maintain the saturation temperature of the working fluid during experiments. There are two Swagelok valves, one on the top (degassing) and one at the bottom (draining). The top valve is connected to an external condenser to minimize loss of the working fluid during the degassing procedure. T-type thermocouples are used to measure liquid, vapor, and test heater temperatures. The internal pressure is measured by an absolute pressure transducer, Omega PX202, which has a range of 0–30 psi.

2.2 Test Heater Preparation

Plain Heater (uncoated):

A schematic of the heater assembly used for the pool boiling tests is shown in Fig. 1(b). The test heater consists of a square copper block, a heating element, lexan substrate, epoxy, and wires. The 1 cm square resistor (20 Ω) is soldered to the copper block (1 cm \times 1 cm \times 0.3 cm). The copper block and resistor assembly are then placed on the lexan substrate, copper side up. 3M® 1838 Scotch-Weld Epoxy is then distributed around the perimeter of the copper block exposing only the top (1 \times 1 cm²) surface. The epoxy and the substrate also function as insulators by preventing heat loss through the sides and bottom. A T-type thermocouple implanted in the copper block measures the temperature. The thermocouple is located 1.5 mm below the heater surface and the surface temperature is calculated assuming one-dimensional, steady-state conduction.

Nanoparticle coated heater (nanocoated):

The nanoparticle coated heater is made from the same plain heater just described. The nanoparticle coating is generated by boiling the plain heater in ethanol-based nanofluid. The ethanol nanofluid solution is prepared by adding 2 g of Al_2O_3 nanoparticles into 2 l of ethanol (resulting in nanofluid concentration of 1 g/l) and then subjecting it to an ultrasonic bath for two hours. The plain heater is immersed into this nanofluid and a constant heat flux (500 kW/m²) is applied for 2 min. The boiling process results in a thin layer of nanoparticle deposition and once this coating is developed, the heater is flushed with pure ethanol and dried with an air jet. This heater is optimal in that it maximizes CHF without degrading the BHT during pool boiling in pure water. The rationale in

selecting the ethanol-based nanofluid, heat flux, and time is described by Kwark et al. [17].

2.3 Working Fluids Preparation

As mentioned earlier, two soluble substances, boric acid and NaCl , were used as additives. Both were provided by Alfa Aesar, having 99.99% purity. The given densities were 1.435 g/cm^3 and 2.165 g/cm^3 for boric acid and NaCl , respectively. The working fluids were prepared by weighing appropriate quantities of both particles using an Acculab VI-1mg precision balance and then diluting them into 3.5 liters of deionized-distilled water. The solutions were then subjected to a magnetic stirring bath for a half hour using RH Basic KT/C (IKA Inc.). To expedite the dilution process, the bath was heated and kept at $\sim 50^\circ\text{C}$ during the stirring process since particle diffusion speed is proportional to the temperature. In particular, the solubility of boric acid in water is very low at room temperature ($\sim 47 \text{ g/l} \approx 3.3\% \text{ vol.}$) when compared to NaCl ($\sim 360 \text{ g/l} \approx 16\% \text{ vol.}$). Therefore, heat is required to

prepare well diluted 5% vol. borated water. With this, prepared 3.5 liters of borated and NaCl water were ready for the pool boiling experiments. The concentrations used in present study varied from 0.5% to 5% vol.

2.4 Experimental Procedures

Pool boiling tests of borated and NaCl water were performed using the apparatus and heater shown in Fig. 1. Before each test, the test vessel was thoroughly washed using distilled water and the heater was then mounted securely within the test section. A preliminary test was then run using pure water to verify that the experimental vessel was not contaminated by additives (boric acid and NaCl) from the previous test. After this pre-test, the prepared working fluid was poured into the test vessel. Once the vessel was tightly sealed, the cartridge heaters were turned on and the valve on the top of the vessel was opened to release non-condensable gases contained within the vessel and dissolved in the working fluids. The system temperature was increased till the liquid temperature

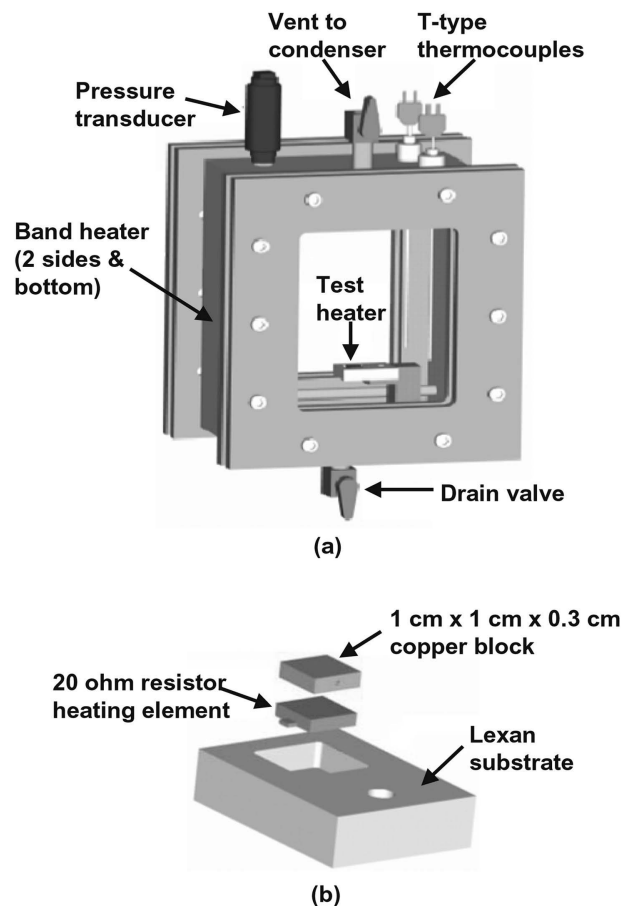


Fig. 1. Schematics of (a) Test Facility (b) Test Heater Assembly.

reached its saturation temperature and was maintained at this value for 30 min. to remove the non-condensable gases in the test liquid. The condenser, located above the test section, allows non-condensable gases to escape while simultaneously condensing any vapor back into the vessel to maintain the initial additive concentration. After 30 min., the top valve was closed and the cartridge heaters were turned off. The system pressure was then checked to insure it equaled the saturation pressure corresponding to the liquid temperature. At this point, a temperature controller which is connected to external band heaters was activated to maintain constant system temperatures. Tests were started after allowing the working fluid temperature to level off at a constant value ($T_{\text{sat}} \approx 100^\circ\text{C}$).

A LabVIEW program controlled a power supply and data acquisition system. The heat flux was increased at constant increments till the CHF condition was reached. The program evaluated the heater temperature for steady-state equilibrium at each applied heat flux before increasing the heat flux to the next programmed increment. The program assumed that the CHF condition was reached when the temperature of the heater exceeded the previously recorded temperature by more than 20°C . The power to the heater was then shut off and all data including temperatures, pressure and heat flux were saved.

2.5 Experimental Uncertainty

The methods described in Kline and McClintock were used to estimate uncertainty [19]. Considering errors due to voltage, surface area of the heater and the current applied, the heat flux uncertainty was estimated to be less than 5%. The temperature and the pressure measurements were estimated to have less than $\pm 0.5^\circ\text{C}$ error and $\pm 0.25\%$ error in full scale considering calibration error, respectively. Weight measurements of additives were estimated to have less than ± 0.01 g error. Uncertainty in liquid volume measurements was estimated to be less than ± 35 ml.

3. RESULTS AND DISCUSSION

In this study, two soluble additives (boric acid and NaCl) were diluted in water and the solutions were used as the working fluids to study the effects of the additives in pool boiling heat transfer. Both uncoated and nanocoated heaters were tested. The nanocoating was developed as described earlier. Due to the lack of comparable data on the pool boiling of additive solutions, CHF and BHT results obtained from the present study were compared to those given on previous nanofluid reports [16, 17].

3.1 Effect of Nanofluids with the Uncoated Heater

Previously, Kwark et al. [16] have shown that the addition of nanoparticles to the base fluid, at low concentrations ($\leq 2.7 \times 10^{-1} \%$ vol.) significantly enhances

the CHF value. Pool boiling curves for these nanofluid experiments as well as a pool boiling curve for pure water are provided in Fig. 2.

In Fig. 2, the boiling curve and the CHF value of pure water show good agreement with Rohsenow's correlation [20] for a polished copper surface ($C_{\text{sf}} = 0.0128$ [21]) and with Zuber's CHF correlation [22] ($1,110 \text{ kW/m}^2$, the termination point of the Rohsenow curve), respectively. In these results, the first two concentrations, $1.3 \times 10^{-3} \%$ vol. (0.005 g/l) and $6.7 \times 10^{-3} \%$ vol. (0.025 g/l), show that as the nanoparticle concentration increases, the CHF value also increases and the pool boiling curve closely follows the boiling curve for pure water. This indicates that at these concentrations there is no degradation in BHT of the nanofluid relative to pure water. The CHF value shows a maximum increase of $\sim 80\%$ over Zuber's correlation [22] at $6.7 \times 10^{-3} \%$ vol. (0.025 g/l).

The remaining two concentrations, $2.7 \times 10^{-2} \%$ vol. (0.1 g/l) and $2.7 \times 10^{-1} \%$ vol. (1 g/l) in Fig. 2, demonstrate the effect of relatively high nanoparticle concentration ($> 2.7 \times 10^{-2} \%$ vol.) on nanofluid boiling performance. Although the CHF value remains about the same as that obtained for $2.7 \times 10^{-2} \%$ vol. concentration, the boiling curve separates at some point from the boiling curve obtained for pure water, thereby showing that BHT degrades. The separation distance increases with heat flux in this test and has been shown to increase also with increased concentration [16]. Kwark et al. [15] attributed the appearance of BHT degradation to the transient characteristics of nanofluid pool boiling. During boiling,

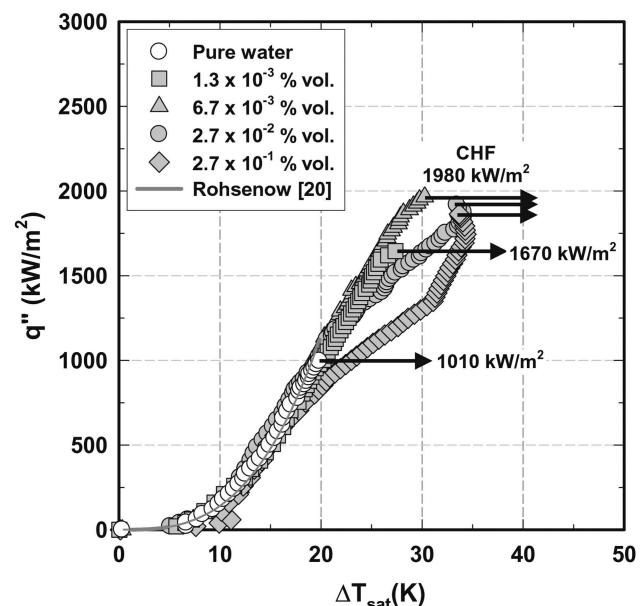


Fig. 2. Pool Boiling Curves for Al_2O_3 Nanofluids ($1.3 \times 10^{-3} - 2.7 \times 10^{-1} \%$ vol.) Obtained by Kwark et al. [16].

the heater surface is continuously modified by the nanoparticle deposition, making nanofluid pool boiling performance a time-dependent process. The magnitude of this deterioration increases with an increase in the applied power, concentration, and testing time. Moreover, Kwark et al. [15, 16] experimentally showed that microlayer evaporation produces the nanoparticle coating on the heater surface and that the coating then changes the surface wetting characteristics which then increases CHF.

The CHF value in the nanofluid over Zuber's [22] CHF value in pure water is plotted versus nanoparticle concentration in Fig. 3. Fig. 3 includes results obtained by You et al. [3], Moreno et al. [7] and Kwark et al. [16]. Kwark et al. [16] carried their experiments at atmospheric pressure ($T_{\text{sat}}=100^\circ\text{C}$) and the former two researchers at a lower pressure ($T_{\text{sat}}=60^\circ\text{C}$). Even though the pressures were different, the results indicate that increasing concentration increases CHF until a concentration of about $6.7 \times 10^{-3} \% \text{ vol.}$ (0.025 g/l). Increasing the concentration beyond this value does not affect CHF enhancement. These studies demonstrate that a concentration of $6.7 \times 10^{-3} \% \text{ vol.}$ (0.025 g/l) provides maximum CHF enhancement without degrading BHT.

3.2 Effect of Borated and NaCl Water with the Uncoated Heater

Instead of nanofluids, pool boiling experiments were conducted using borated and NaCl water with the uncoated (plain) heater. First, the uncoated surface (plain) was tested in various concentrations of borated water (0.5~5% vol.).

Fig. 4 shows that at a concentration of 0.5% vol. the CHF increases while the pool boiling curve closely follows the curve for pure water. This indicates that up to this concentration, the BHT is almost identical to that of pure water. The CHF, on the other hand, increases further with increasing boric acid concentration until eventually leveling off at a value of $\sim 2,000 \text{ kW/m}^2$. Thus, borated water provides a CHF which is up to about 80% greater than that predicted by Zuber's correlation [22] for pure water at 1 atm. For concentrations beyond 0.5% vol., the pool boiling curves break away from the boiling curve of pure water. This separation increases with increasing concentration indicating a marked decrease in BHT. The CHF enhancement and BHT deviation behaviors observed are very similar to those of nanofluids reported by Kwark et al. [16]. As previously shown in Fig. 2, the CHF value increased as the nanofluid concentration increased until CHF leveled off, and BHT performance degraded beyond the critical concentration of $6.7 \times 10^{-3} \% \text{ vol.}$ A difference between the nanofluid and borated water is that the borated water seems to require much higher concentration, about two orders of magnitude larger, than that in nanofluids to obtain similar CHF enhancement because of the soluble nature of the boric acid. Interestingly, however, the

maximum CHF enhancement obtained in nanofluids and borated water is almost identical, leveling off at $\sim 2,000 \text{ kW/m}^2$.

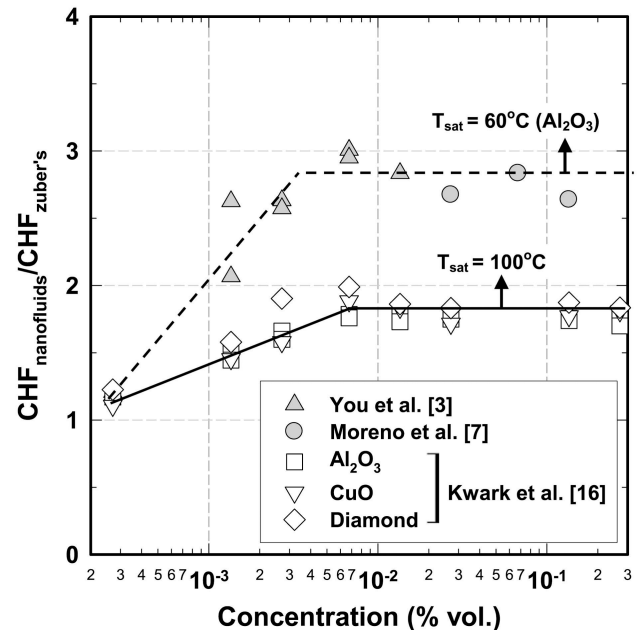


Fig. 3. CHF Enhancement of Various Nanofluids, Defined as the Ratio of Nanofluid CHF Over Water CHF as Predicted by Zuber's Correlation [22], by You et al. [3], Moreno et al. [7], and Kwark et al. [16].

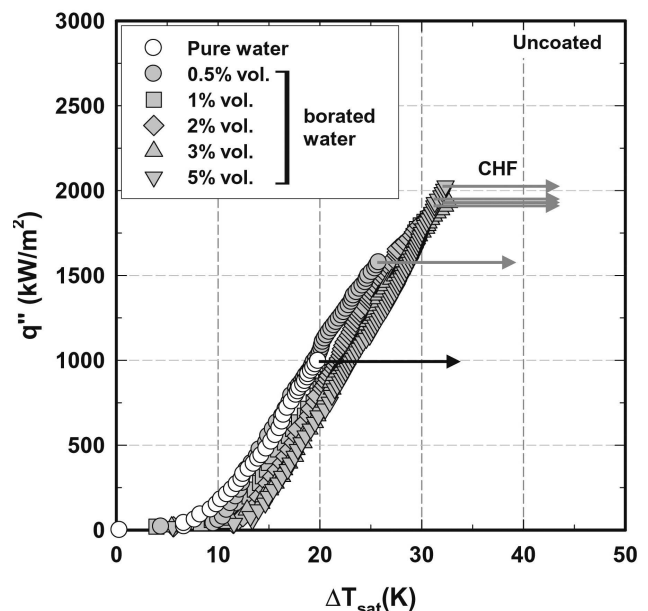


Fig. 4. Pool Boiling Curves of Borated Water (0.5 - 5% vol.) with the Uncoated Surface.

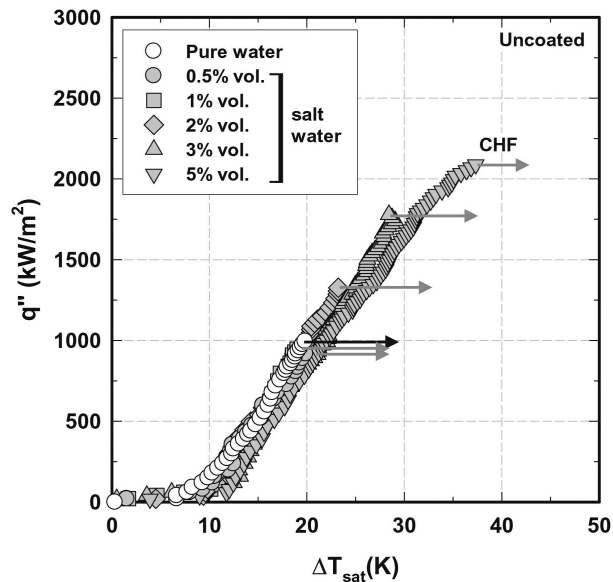
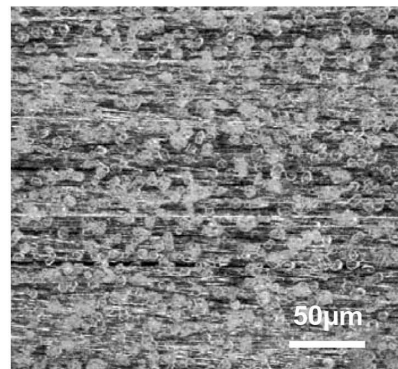


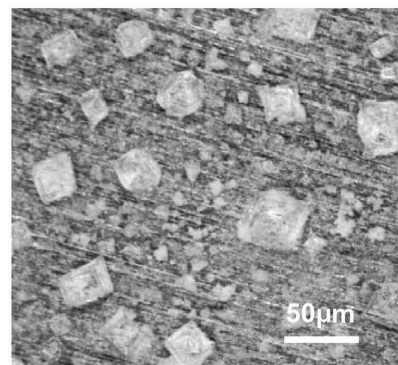
Fig. 5. Pool Boiling Curves of NaCl Water (0.5 - 5% vol.) with the Uncoated Surface.

Similar pool boiling experiments were conducted with NaCl water and the results are shown in Fig. 5. From the result, it can be noted that trends of CHF enhancement and BHT degradation were almost identical to those of the borated water experiment. The CHF value of NaCl water increases with concentration and the BHT curve closely follows the boiling curve of pure water for 1% and 2% vol. concentration. Then, BHT begins to deteriorate at 3% vol. concentration. Since it was believed that the CHF enhancement would level off at higher concentration, no tests were carried out for concentrations beyond 5%.

These two additive studies demonstrate the similarity between nanofluids and solid solubles in water. Soluble additives (boric acid and NaCl) can also enhance CHF significantly. As discussed earlier, recent studies [9, 10, 13, 16] have shown that the nanoparticle coating developed during nanofluid boiling was the sole source of CHF enhancement, and that the better wettability of the nanocoated surface was responsible for the enhancement [9, 16]. The degradation of BHT with increased nanoparticle concentration was attributed to the corresponding thicker coating that was created which in turn increased the thermal resistance [17]. Since the boiling performance of diluted additive water was also influenced by additive concentration, it was believed that the heater surface was also modified by soluble particles, resulting in CHF enhancement and BHT degradation. Optical microscope images of the heaters were taken after they were tested in pool boiling in borated and NaCl water, and are shown in Fig. 6. Boric acid and NaCl particle deposition can be observed on these test surfaces. In conclusion, a deposition process



After borated water test (1% vol.)



After NaCl water test (5% vol.)

Fig. 6. Optical Images of Coatings (Boric Acid and NaCl) Developed During Boiling Experiments.

(through microlayer evaporation) during boiling tests is believed to take place even when the particles are soluble and the developed coating most probably enhances the surface wettability. If so, this wetting enhancement would play a pivotal role in CHF enhancement. However, a wetting/wicking study was not possible due to the soluble nature with water of the obtained coatings.

3.3 Effect of Borated and NaCl Water with the Nanocoated Heater

The nanocoated heater used in the present study is optimal in that it maximizes CHF without degrading BHT when pool boiling pure water [17]. Kwark et al. [17] also showed that this optimal nanocoating was reliable for 15 consecutive pool boiling tests in pure water. These results and an image of the nanocoating are shown in Fig. 7. This figure shows that repeating experiments with the same nanocoated heater has no effect on both CHF and BHT. This strongly indicates that the coating has good bonding to the surface.

The nanocoated heater was fabricated and used to carry

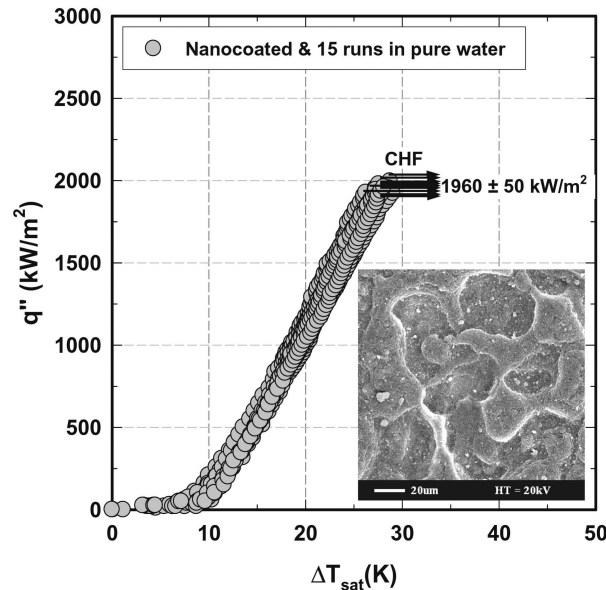


Fig. 7. Kwark et al.'s [17] Reliability Test Result of the Nanocoating, Developed in 1 g/l (2.7×10^{-1} % vol.) Alcohol Nanofluid at 500 kW/m^2 for 2 min. and Tested in Pure Water for 15 Times.

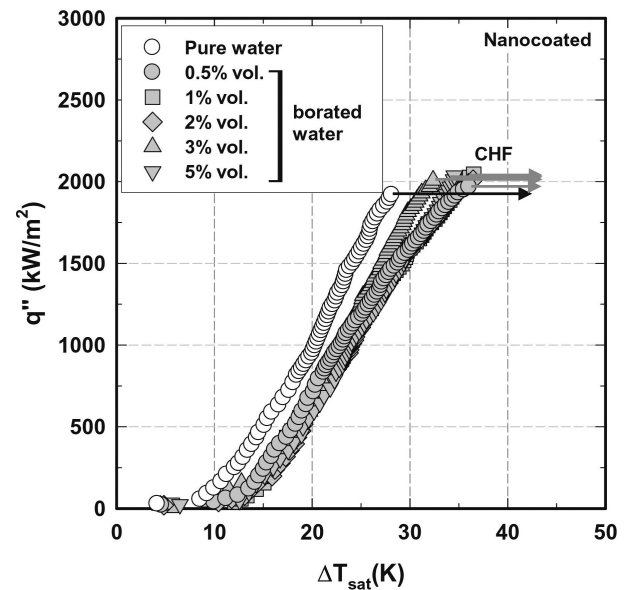


Fig. 8. Pool Boiling Curves of Borated Water (0.5 - 5% vol.) with the Nanocoated Surface.

out boiling experiments in borated and $NaCl$ water. Fig. 8 illustrates the boiling performance of the nanocoated heater in borated water alongside the boiling curve of the nanocoated heater in pure water. Unlike the results of the uncoated surface, the boiling curves always show the maximum CHF enhancement which was obtained by nanocoatings alone in [17]. However, BHT degrades for all concentrations of boric acid. This indicates that there is no further CHF enhancement due to the borated water when it is boiled over the nanocoated surface. Based on the deposition on plain copper which was shown in Fig. 6, it is believed that there is an additional deposition of boric acid on top of the nanocoated surface during boiling experiments, resulting in the current BHT deterioration in Fig 8. The same nanocoating was tested in $NaCl$ water (2~5% vol.) and the pool boiling curves are shown in Fig. 9. Like the result from borated water, no further CHF enhancement is found regardless of the concentration and BHT degradation is also observed at higher concentrations of $NaCl$ water (>3% vol.).

Fig. 10 plots the CHF enhancement, defined as the ratio of the borated and $NaCl$ water CHF (at various concentrations) to the pure water CHF as predicted by Zuber's correlation [22], for plain and nanocoated surfaces. For the same concentrations, the magnitudes of CHF enhancement appear to be markedly different between fluids over the plain surface, and between surfaces with decreasing concentrations. However, for both (boric acid, $NaCl$), increasing the concentration increases CHF until

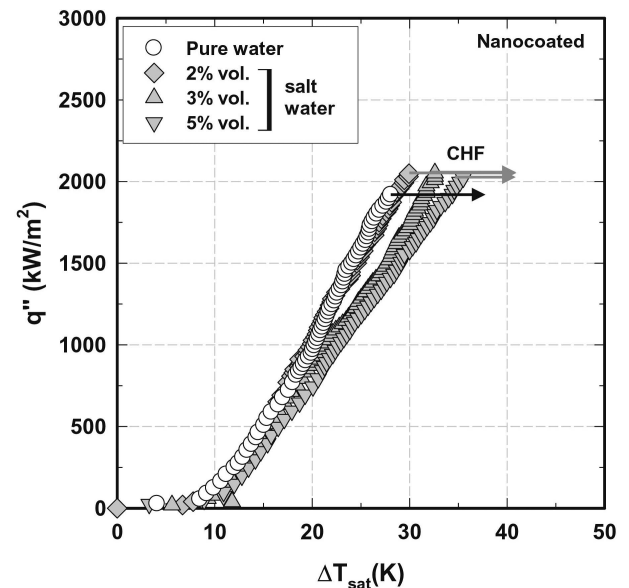


Fig. 9. Pool Boiling Curves of $NaCl$ Water (2 - 5% vol.) with the Nanocoated Surface.

it is ~80% greater than that of Zuber's correlation and then, CHF remains fairly constant at $\sim 2000 \text{ kW/m}^2$. For the nanocoated surface, on the other hand, the result always shows the maximum CHF enhancement (~80%) which is

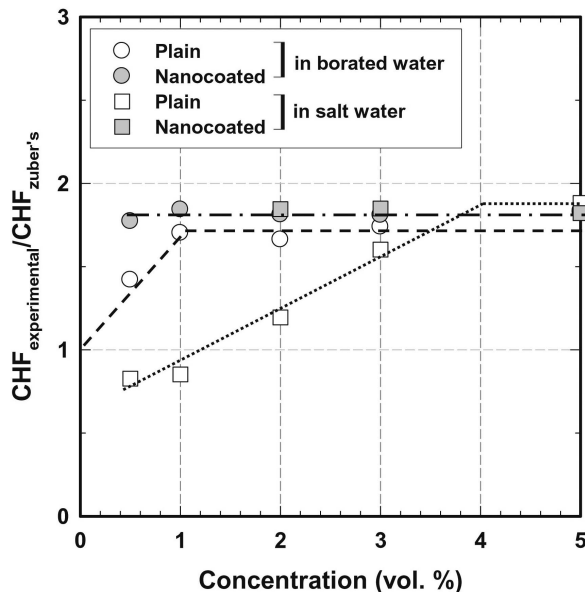


Fig. 10. CHF Enhancement, Defined as the Ratio of Obtained CHF Over Water CHF as Predicted by Zuber's Correlation [22], for Borated and NaCl Water Using Plain and Nanocoated Surfaces.

achieved by the nanocoating in pure water [17]. Also, very similar CHF enhancement, between the borated and NaCl water, is obtained when using the nanocoating. This indicates that, when boiling over a nanocoated heater, the additives (boric acid and NaCl) do not affect the CHF. However, as was observed in Fig. 8 and Fig. 9, the boiling curves separate from that of pure water as concentration increases. In other words, over the nanocoated heater, BHT also degrades with increasing concentration due to the extra deposition of the additives on the boiling heater surfaces.

3.4 Reliability of Additive Coating in Boiling of Pure Water

To confirm the reliability of the coating developed from the solutes, the additive coated heaters were repeatedly tested in pure water. From the boiling results in Fig. 4 and Fig. 5, the maximum CHF was achieved by using concentrations of no less than 1% for borated and 5% for NaCl water. Therefore, the coatings generated from those experiments were used for the reliability test of boric acid and NaCl coatings. Fig. 11 shows the results of pure water pool boiling with the boric acid coating. There is still a noticeable CHF enhancement, by ~35% for the 1st run in pure water, compared to Zuber's estimation [22]. Then, the CHF enhancement is successively reduced with each additional run in pure water. Finally, for the 4th run in pure water, the CHF enhancement is completely gone, meaning that the CHF value is almost the same as Zuber's [22] value (1110 kW/m²) for pure water.

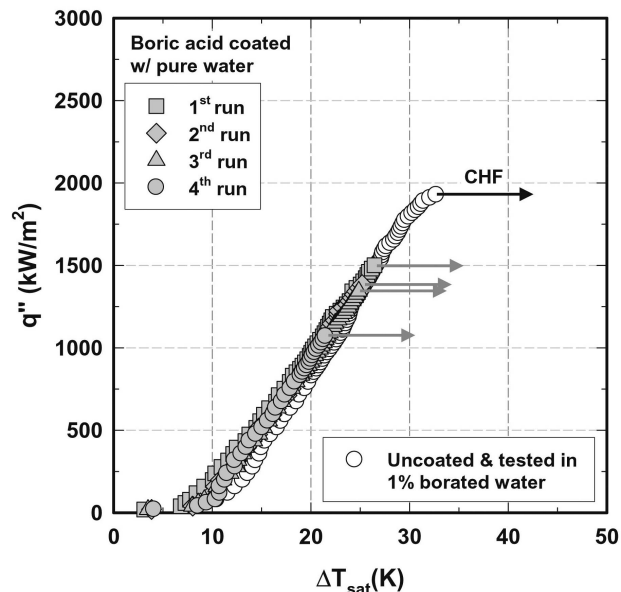


Fig. 11. Pool Boiling Curves of Pure Water with the Boric Acid Coated Surface.

This is dissimilar to the reliability of the nanocoating reported by Kwark et al. [17], which was that it performed consistently for a given period (15 runs in pure water). Unlike the nanoparticle coating, the present coating is made of water-soluble particles, and therefore dissolves into the water during the pure water boiling test. This results in no CHF enhancement after multiple tests in pure water. After the multiple runs, the heater surface was visually examined and it was observed that the deposited material had disappeared from the heater surface.

Likewise, the NaCl coating was tested in pure water and the result is shown in Fig. 12. It can be observed that the CHF enhancement becomes negligible after the 2nd run. Visual inspection confirmed also that the coating had completely disappeared. From these experiments, it seems that the rate of dilution of boric acid and NaCl coatings is different. The boric acid coated heater shows some CHF enhancement up to the 3rd run while the CHF enhancement of the NaCl coating becomes negligible after the 2nd run. Therefore, it is believed that soluble additive coatings eventually dissolve during the pure water boiling experiments, resulting in disappearance of CHF enhancement after multiple runs in pure water.

4. CONCLUSIONS

Pool boiling characteristics of soluble additives in water (0.5–5% vol.) were experimentally studied using uncoated and nanocoated heaters. Two soluble additives

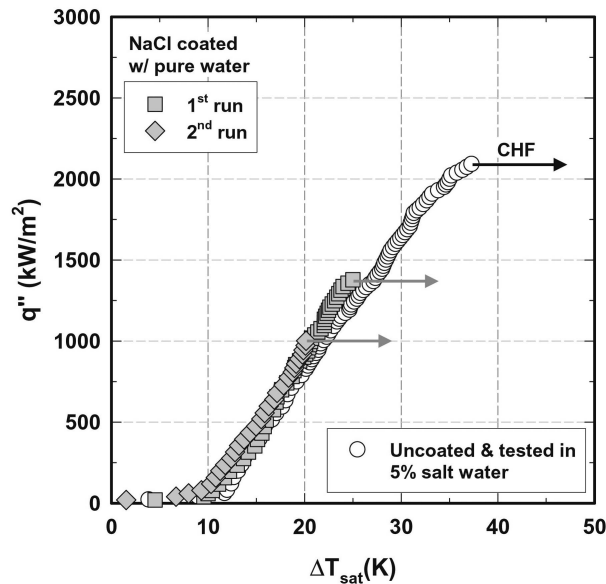


Fig. 12. Pool Boiling Curves of Pure Water with the NaCl Coated Surface.

(boric acid and NaCl) were used and all experiments were conducted at atmospheric pressure. The present study mainly focused on the effect of the additives in pool boiling heat transfer and the results are summarized below.

- Heater surfaces are believed to be modified during the boiling process of water with dissolved additives, resulting in significant CHF enhancement. This is almost the same behavior as that of nanofluid boiling. The present study indicates that even soluble additives are deposited on the heater surface during the boiling process (microlayer evaporation). It is surmised that this surface modification enhances the wettability of the heater surface which in turn significantly increases CHF in water with dissolved additives.
- Tests of the nanoparticle coated surface in water with dissolved additives confirm that there is no interaction of the nanoparticle coating with the soluble particles to further enhance CHF, with the CHF leveling off at $\sim 2000 \text{ kW/m}^2$, which is about the same value obtained when the nanocoating alone is tested in pure water. However, BHT degrades as the additive concentration increases. This indicates that the additional additive layer gets deposited on top of the nanocoating due to continuous microlayer evaporation during the nucleate boiling processes, resulting in BHT deterioration.
- Unlike the nanoparticle coating, the additive coating is soluble in water so that the developed additive coating disappears during pure water boiling experiments. This results in disappearing of CHF enhancement after multiple tests in pure water.

NOMENCLATURE

BHT	boiling heat transfer
CHF	Critical heat flux
q''	heat flux, [kW/m^2]
T	temperature, [$^{\circ}\text{C}$]
ΔT_{sat}	wall superheat, [$T_w - T_{\text{sat}} (P_{\text{sys}})$]

SUBSCRIPTS

sat	saturated conditions
w	wall, heater surface

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