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International Journal of Heat and Mass Transfer 51 (2008) 3025–3031

International Journal of HEAT and MASS TRANSFER

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Wettability of heated surfaces under pool boiling using surfactant solutions and nano-fluids

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Received 15 January 2007; received in revised form 10 September 2007
Available online 19 November 2007

Abstract

The wettability of the heated surface under pool boiling of surfactant solutions and nano-fluids has been investigated. Tri-sodium phosphate (TSP, Na_3PO_4) solutions (0.01, 0.05, 0.1, 0.3, 0.5, 0.8 wt.%) and Aluminum oxide (Al_2O_3) nano-fluids (NF) (0.5, 1, 2, 4 vol.%) were prepared for experiments. Stainless steel (SUS 304) strips ($30 \times 30 \times 3$ mm) were heated by an alcohol lamp and quenched in the prepared solutions. Before complete quenching, when the surface temperature was 150 ± 10 °C (nucleate boiling region), the strip was taken out and excessive liquid on the surface was removed. Contact angles of pure water and the solutions on the quenched surface and fresh surface were measured. Contact angles of pure water on the quenched surfaces (5°–25°) were much smaller than those on the fresh surface (65°–70°). The solutions (TSP, NF) on the quenched surface shows the smallest contact angle (5°–15°). Surfaces deposited TSP and nano-particle could affect surface energy of the strips and enhance hydrophilicity of the surfaces. Several implications of the experimental results on the pool boiling CHF model and CHF enhancement using TSP and NF were discussed.

Keywords: Pool boiling; CHF; Nano-fluids; Wettability

1. Introduction

CHF is the heat transfer limit causing sudden rise in heater surface temperature under a heat flux controlled conditions by the sudden decrease of heat transfer by dry-out of heat transfer surface. CHF limits the heat transfer of a heat transfer system and thus CHF enhancement is directly related to the performance of the system. There have been many researches to find appropriate CHF enhancement methods, such as surface roughening, surface coating, using surfactant solutions and nano-fluids, etc. In the aspect of heat transfer surface, surface roughening and coating were major method to enhance CHF. In the aspect of heat transfer fluid, soluble additives and nano-fluid were used for CHF enhancement.

Surface roughness effect on pool boiling CHF was studied by many researchers [1–3]. It is known that the CHF increases for most of the roughened surface with respect to the fresh and smooth surface. Due to the enlarged effective heat transfer area, heat transfer and CHF increased.

Another important surface treatment for the CHF enhancement is surface porous coating. Metallic or ceramic porous coatings techniques have been adopted for enhancing CHF and many studies have investigated the coating effect on the CHF enhancement [4–10]. CHF enhancement is due to enhanced liquid supply to the heating surface by capillary assisted liquid flow towards a heating surface for the porous coating.

Other than the porous coatings, other coating methods to enhance the surface wettability were studied. Takata et al. [11,12] applied TiO_2 coating to the surface and made superhydrophilic surface by UV irradiation. Due to highly enhanced wettability, CHF was enhanced by a factor of two. They suggested that the superhydrophilic surface can be an ideal heat transfer surface.

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2007.09.023

Nomenclature

q''_{CHF}	critical heat flux (kW/m^2)	*Greek symbols*	
h_{fg}	latent heat of vaporization (kJ/kg)	ρ_g	vapor density (kg/m^3)
g	gravity (m/s^2)	ρ_l	liquid density (kg/m^3)
		σ	Surface tension (N/m)

Soluble additives such as TSP, sodium lauryl sulfate (SLS), sodium lauryl benzene sulfonate (SLBS) were used for CHF enhancement [13,14]. The CHF enhancement was explained by the change of bubble shape and motion on boiling surface.

Recently, relationship between CHF and nano-fluid was studied by many researchers [15–19]. The results show that the nano-fluids significantly enhanced pool boiling CHF compared to pure water. It was supposed that CHF enhancement was due to increased thermal conductivity of fluids, change of bubble shape and behavior, nano-particle coating of the boiling surface.

In this study, conditions of heated surface in pool boiling of pure water, TSP solutions and nano-fluids were investigated. To examine the surface conditions, test specimens were heated and quenched in water and solutions. After taking out the specimens out of liquids, contact angles of liquids on quenched specimens were measured and interpreted as an index of surface wettability. Alternation of surface conditions by deposition of TSP and nano-particle were observed and their effect on surface wettability was quantified. It is concluded that the increase of CHF by TSP solutions and nano-fluids might be due to highly increased wettability of the TSP and nano-particle deposited surfaces. Implications of the results to CHF model were also discussed.

2. Experiments

The test pool was 12 l capacity poly propylene container and it was filled with TSP solutions or alumina–water nano-fluids both at 25 °C, under atmospheric pressure.

Test specimen made of SS304 (30 × 30 × 3 mm) and mirror-like polished was heated by alcohol lamp up to 400 °C and quenched in pure water, TSP solutions and nano-fluids. Before complete quenching, when the surface temperature was 150 ± 10 °C (nucleate boiling region), the strip was taken out and excessive liquid on the surface was removed. Temperature was measured by Type-K thermocouple (outer diameter 0.5 mm). For understanding effect of quenching temperature, specimens were also taken out at various temperatures.

Tri-sodium phosphate (TSP, Na_3PO_4) surfactant was added to the pure water. TSP is an additive to a spray system or sump water of nuclear power plant for maintaining high pH level during accidents. Experiment was performed with six different concentrations: solutions with 0.01%, 0.05%, 0.1%, 0.3%, 0.5%, 0.8% mass faction. Prepared TSP solution was filled in the test pool and the heated test specimen was quenched in the pool.

Alumina nano-fluids were prepared by dispersing alumina nano-particles into pure water. In order to make uniform nano-fluids, the solutions were pre-processed in an ultrasonic bath for about 1 h just before the each test. Due to the ultrasonic energy, the solution temperatures increase from 25 °C to about 35 °C. After cooling the test pool, tests were made at 25 °C. Four nano-fluids were prepared and used in quenching tests: solutions with 0.5%, 1.0%, 2.0%, 4.0% volume fraction (47 nm avg., normal distribution in range of 4–124 nm diameter).

Solution quenched specimens were made by quenching specimens in the TSP and nano-solutions. Water quenched specimens were made by quenching specimens in pure water. After quenching tests, the contact angle of liquid (pure water, TSP solutions and nano-fluids) on the quenched surfaces were measured. Contact angles were measured by sessile drop tests using the contact angle measurement instrument KRÜSS DSA10. Range of contact angle measurements was 1°–180° and resolution was 0.1°. Temperature of droplet is 20 °C in all experiments. Sessile drop test is the standard method for quick and accurate wetting test. The deposited drop lies on the surface and forms a contact angle that depends on the properties of the three phases: drop liquid, solid and surrounding phase. The probe fluids used were pure water and nano-fluids with drop volumes of 15 μL. Solid surfaces were: (1) un-heated fresh surface, (2) water quenched surface, (3) TSP quenched surfaces and (4) nano-fluid quenched surfaces. Solid surface were also examined by video microscope EG Tech EGVMS35.

3. Results and discussion

3.1. Visual observation

Visual observation was performed to understand the phenomenon on surface when the nucleate boiling occurred. Fresh surface, water quenched surfaces, TSP quenched surfaces and nano-fluid quenched surfaces were observed by video microscope and digital camera. As shown in Fig. 1, TSP and nano-particles were deposited on the heated surfaces. The take-out temperature was about 150 °C. On the nano-fluid quenched surfaces, nucleation sites were clearly observed. On the TSP solution

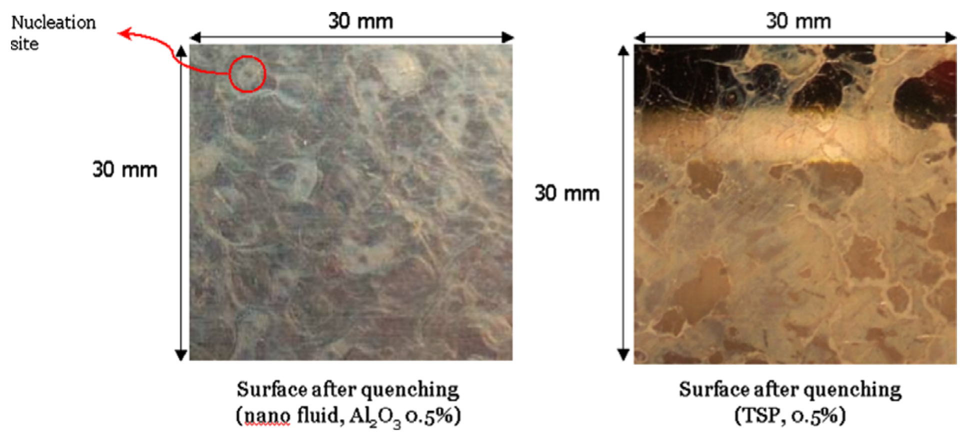


Fig. 1. Picture of quenched surfaces ($T_{\text{take-out}} = 150$ °C).

quenched surfaces, there was a pattern of deposition, but less clear than that of nano-fluid quenched surfaces. For the take-out temperature of 300 °C or more (up to 400 °C), there was no deposition on the both of quenched surfaces: TSP solution quenched and nano-fluid quenched. At this high temperature, as known as Leidenfrost phenomenon, liquid cannot directly contact with the hot surface and heat transfer is driven only by radiation from hot surface to cold liquid. As there was no direct contact between liquid and surface, no deposition might be observed. For the take-out temperature of 100 °C or less, because the surface temperature was below the boiling temperature of the solutions, the deposited TSP and nano-particle during the boiling was washed away by the continuous contact of liquid and surface. Take-out temperature from 150 to 200 °C was optimal to observe the surface condition under nucleate boiling.

As the concentration of nano-fluids increased, the amount of deposited nano-particles increased (Fig. 2). Evidences of nucleation sites can be clearly identified from the visual observations. As Kim et al. [18] observed, nano-particles were deposited on the heater surface and made a layer of coating.

For the TSP solution quenched surfaces, there were evidences of nucleation, but those could not easily be identified (Fig. 3). However, the evidence of TSP deposition was clear.

As mentioned above, from the visual observations, deposition of TSP and nano-particles during the process of nucleate boiling were confirmed.

3.2. Contact angle measurement

In order to investigate the effect of deposited TSP and nano-particles on CHF, contact angle of liquid on the quenched surfaces were measured. Contact angle is an index of hydrophilicity of surface to liquid. As noted in the literatures [11,12], contact angle is important index of wettability and CHF. As contact angle decreases, wettability increases and CHF tends to increase.

In this study, contact angle of various liquids (pure water, TSP solutions and nano-fluids) on fresh and quenched surface were measured by sessile drop tests using DSA 10 contact angle measurement system.

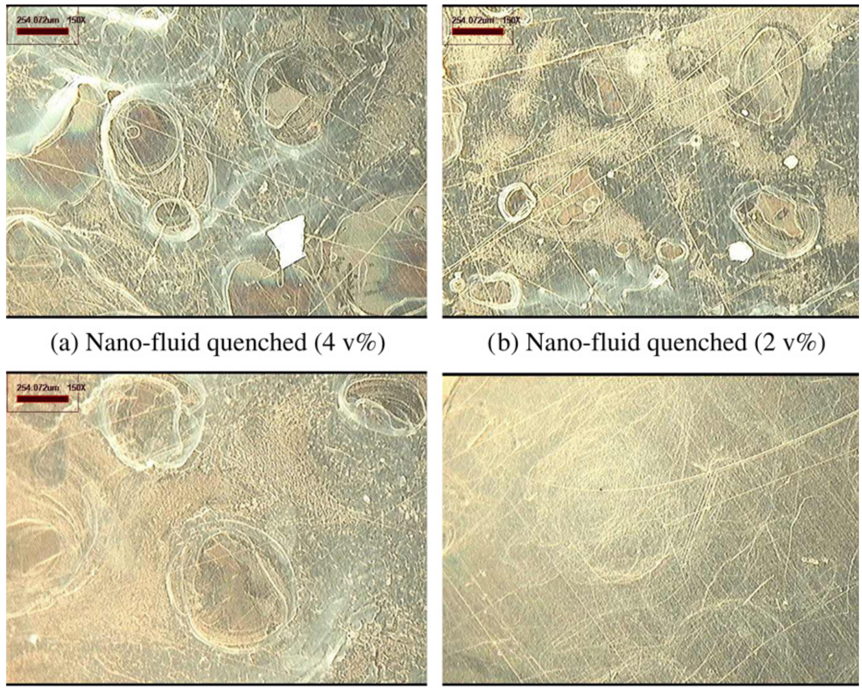
3.2.1. Comparison between fresh surface and water quenched surface

Contact angles of water on a non-heated and not-quenched fresh surface and water quenched surface were measured. As shown in Fig. 4, there was not much difference between the fresh surface and water quenched surface: 73.9° and 69.4°. As Theofanous et al. [20] noted, heavily aged (oxidized) copper surface showed low contact angle and resulted in higher CHF up to 2 times than that of fresh surface. However, in this study, SS304 was used and there was no considerable oxidation. Therefore, there was no significant contact angle change was observed: from 73.9° and 69.4°.

3.2.2. Contact angles on TSP solution and nano-fluid quenched surfaces

Contact angles of water on the TSP solution quenched and nano-fluid quenched surfaces showed significant drop compared to those on the water quenched surface (Fig. 4). It can be interpreted that the hydrophilicity of the quenched surface was highly enhanced. The one and only difference between water quenched surface and solution quenched surfaces is the existence of deposited TSP or nano-particles as observed in the post-quenching observations. Other factors, take-out temperature, liquid temperature, parameters of sessile drop test and the physical property of base material (SS304) remained the same. Therefore, the enhancement of wettability is an effect of the deposited TSP and nano-particles.

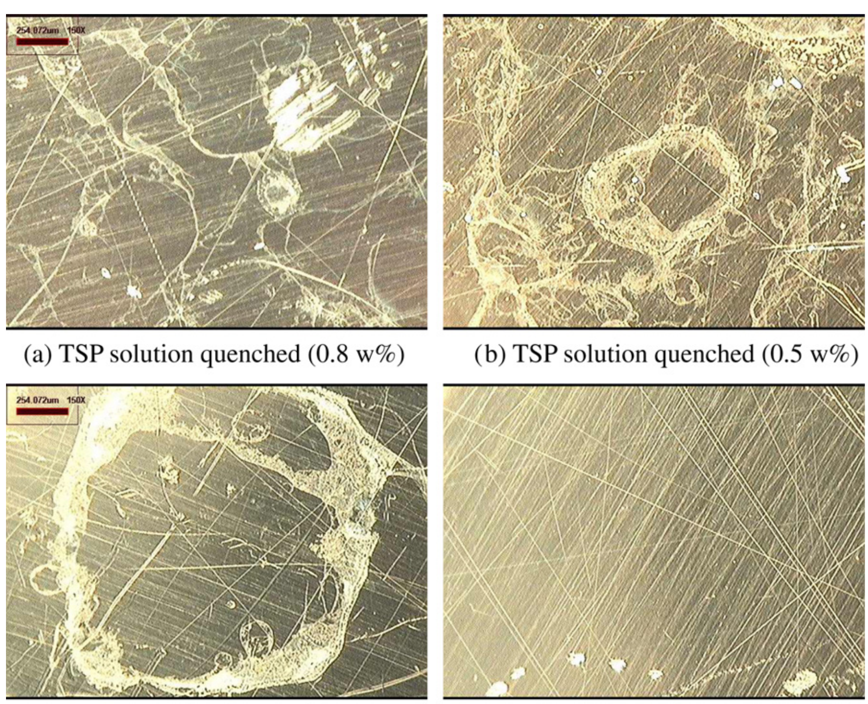
As mentioned above, take-out temperature affected the deposition of TSP and nano-particles. In Fig. 5, the effect of take-out temperature is depicted. At the high take-out temperature (~300 °C), there was no considerably deposited material on the surface due to the Leidenfrost phenom-



(a) Nano-fluid quenched (4 v%) (b) Nano-fluid quenched (2 v%)

(c) Nano-fluid quenched (1 v%) (d) Nano-fluid quenched (0.5 v%)

Fig. 2. Microscope observation of nano-fluid quenched surfaces (150 times magnified, , scale bar = 254 μm).



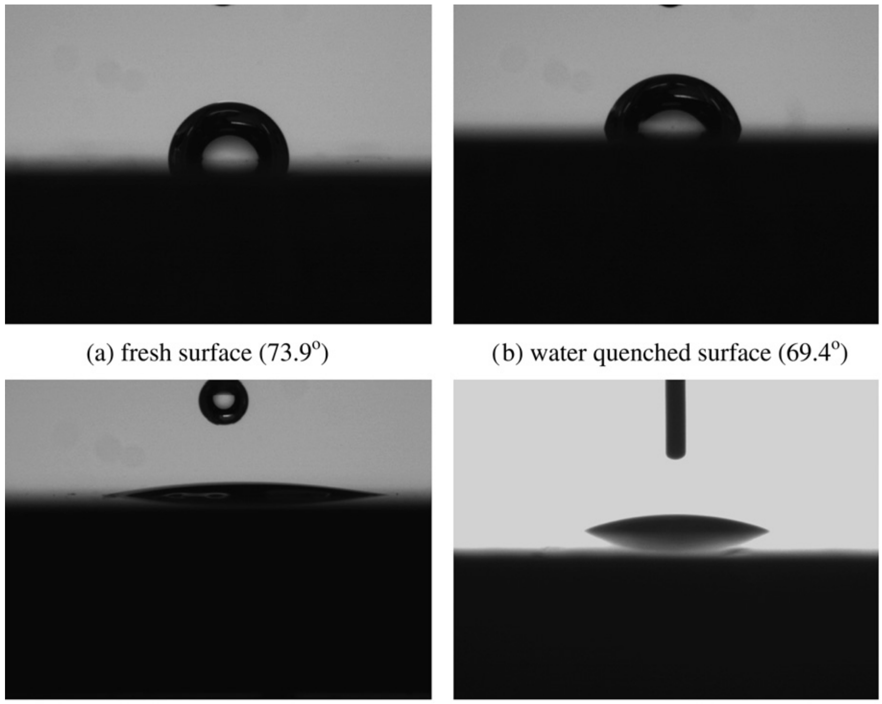
(a) TSP solution quenched (0.8 w%) (b) TSP solution quenched (0.5 w%)

(c) TSP solution quenched (0.3 w%) (d) TSP solution quenched (0.1 w%)

Fig. 3. Microscope observation of TSP solution quenched surfaces (150 times magnified, scale bar = 254 μm).

enon and thus contact angle approaches that of water quenched surface.

By measuring the contact angles, the wettability change by TSP and nano-particle deposition was quantified (Figs. 6 and 7). As shown in the figures, as the concentration of TSP solutions and nano-fluids increased, the corresponding contact angle of water on the quenched surfaces decreased. For the nano-fluid quenched surfaces, contact angle



(a) fresh surface (73.9°) (b) water quenched surface (69.4°)

(c) TSP quenched surface (0.5%, 13.4°) (d) Nano-fluid quenched surface (2%, 20.4°)

Fig. 4. Contact angle measurement of fresh and quenched surface.

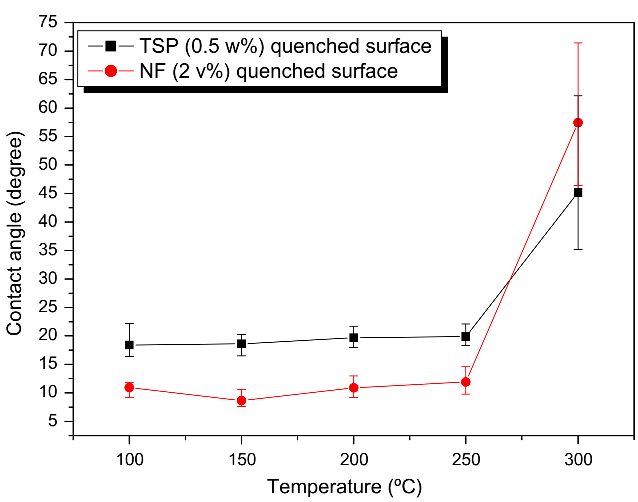


Fig. 5. Contact angle and take-out temperature.

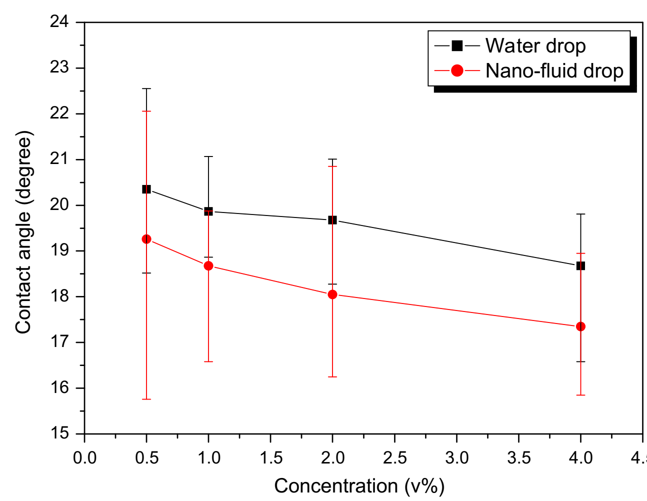


Fig. 6. Contact angle and concentration of nano-fluids ($T_{\text{take-out}} = 150$ °C).

decreased monotonically. However, in the TSP solution quenched tests, there was sudden decrease of contact angle between 0.01 and 0.05 wt.% (Fig. 7). From 0.05 to 0.8 wt.%, there was monotonic decrease as observed in the nano-fluid quenched case. 0.01 wt.% of TSP might be too low to see the considerable effect of TSP addition to water. However, the contact angle of water on 0.01 wt.% TSP solution quenched surface was 24.5° and it was considerably lower than that on the water quenched surface (69.4°).

In addition to the water drop test on the quenched surfaces, nano-fluid drop test to measure the contact angle of nano-fluid on the nano-fluid quenched surface was performed. During the process of nano-fluid pool boiling, the heated surface has deposited nano-particles on it and nano-fluid interacts with the surface. This configuration is very similar to the combination of nano-fluid drop on the nano-fluid quenched surface. As shown in Fig. 6, there was further decrease in the contact angle compared to the water drop tests. This implies that the surface wettability is not only affected by the surface condition but also by fluid property.

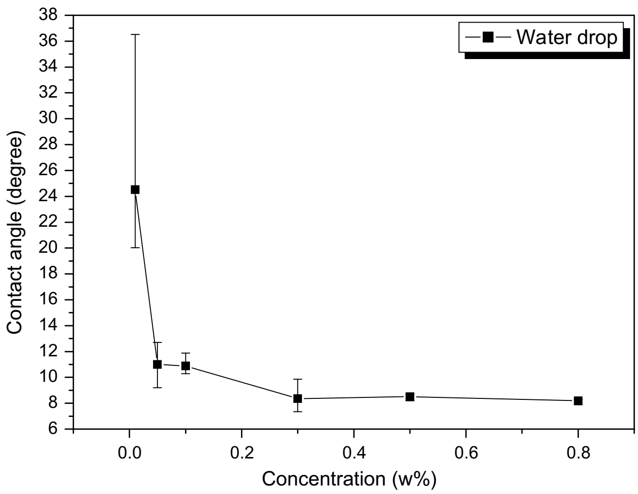


Fig. 7. Contact angle and concentration of TSP solutions ($T_{\text{take-out}} = 150$ °C).

From the results above, the surface deposited TSP and nano-particles considerably promote the wettability of the surface. Although there were differences in a degree of enhancement, previous pool boiling experiments showed enhanced CHF with TSP solutions and nano-fluids [13,16–18]. The underneath mechanism of the CHF enhancement, there might be a role of deposited TSP and nano-particles which considerably enhance the wettability of the surface.

3.3. Contact angle and surface tension

To quantify the surface tension force of TSP solutions and nano-fluids, contact angles of liquids on the Teflon FEP strip were measured. To measure the liquid surface tension, the surface energy of solid should be known. Kwok and Neumann [21] quantified surface energy of several materials by comprehensive experimental work. They also provided modified equations for interpretation of contact angle in terms of surface tension. In this study, the suggested equation and provided surface energy of Teflon FEP was used and the surface tensions of TSP solutions and nano-fluids were calculated. Results are shown in Table 1. Surface tension decreases as the concentration of TSP solutions and nano-fluids increases. The surface tension of pure water at 25 °C is 75 mN/m.

The decreased surface tension of TSP solutions and nano-fluids can affects the dynamics of two-phase mixture. The well-known Zuber's hydrodynamic instability CHF model arrived at the following expression [22]:

$$q''_{\text{CHF}} = 0.131 h_{fg} \rho_g^{1/2} (\sigma g (\rho_l - \rho_g))^{1/4} \tag{1}$$

CHF should be decreased as the surface tension of fluid decreases in Eq. (1). However, CHF of TSP solutions and nano-fluids which has lower surface tension compared to pure water is higher than that of pure water. This result implies the need of modified model to accommodate the effect of heater surface. Kandlikar [23] suggested a theoretical model which can incorporate the effect of contact angle on CHF:

Table 1
Surface tension of TSP solutions and nano-fluids

Fluids	Surface tension (mN/m)		
	Antonow's rule[a]	Modified Berthelot's rule[a]	Alternative Formulation [a]
TSP 0.01 wt.%	69.28	71.12	71.63
TSP 0.05 wt.%	55.34	59.46	60.75
TSP 0.1 wt.%	53.67	57.8	59.13
TSP 0.3 wt.%	47.83	51.54	52.86
TSP 0.5 wt.%	44.40	47.26	48.47
TSP 0.8 wt.%	46.53	49.89	51.17
NF 0.5 wt.%	63.86	67.00	67.9
NF 1 vol.%	57.60	61.61	62.83
NF 2 vol.%	55.41	59.53	60.82
NF 4 vol.%	54.38	58.51	59.83

Note: Surface tension of pure water at 25 °C is 75 mN/m.
[a] Ref. [21].

$$q''_{\text{CHF}} = h_{fg} \rho_g^{1/2} \left(\frac{1+\cos\beta}{16}\right) \left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\beta)\cos\phi\right]^{1/2} \times [\sigma g (\rho_l - \rho_g)]^{1/4} \tag{2}$$

where β is contact angle of liquid on solid surface and ϕ is orientation of surface (horizontal is set to 0). In Eq. (2), contact angle and surface tension terms compete each other. Contact angle terms imply surface wettability and liquid surface tension term implies hydrodynamic instability. Decrease of contact angle increases the CHF while decrease of liquid surface tension decreases the CHF. However, the effect of contact angle is more dominant than the effect of surface tension and thus CHF can be enhanced in TSP solutions and nano-fluids. For example, liquid surface tension of 4 vol.% nano-fluid is 58.5 mN/m and contact angle of 4 vol.% nano-fluid on 4 vol.% nano-fluid quenched surface is 17.35°. Cos(17.35°) is 0.955. Those of pure water are 75 mN/m, 69.4° and 0.352. The surface tension decreased by 22% while cosine of the contact angle increased by 170%. And, exponent of contact angle term is 3/2 while that of surface tension is 1/4. However, to understand the combined effect of surface tension (hydrodynamic instability) and contact angle (surface wettability) more exactly, a comprehensive experimental work followed by theoretical modeling would be necessary.

4. Conclusions

In this study, wettability of heater surfaces in pool boiling of TSP solutions and nano-fluids was investigated by quenching experiments. Through the visual observation of quenched surfaces, deposition of TSP and nano-particle was observed. Through the measurement of contact angle of liquid on the quenched surfaces, it is concluded that the surface deposited TSP and nano-particles enhanced wettability of the surface. Several implications of the experimental results on the pool boiling CHF model and CHF enhancement using TSP and NF were discussed: There is need of experiments and theoretical modeling which can accommodate hydrodynamic instability and surface wettability in a comprehensive manner.

References

[1] J.Y. Jung, H.Y. Kwak, Effect of surface condition on boiling heat transfer from silicon chip with submicron-scale roughness, Int. J. Heat Mass Transfer 49 (23/24) (2006) 4543–4551.
[2] K. Ferjancic, I. Golobic, Surface effects on pool boiling CHF, Exp. Thermal Fluid Sci. 25 (7) (2002) 565–571.
[3] J.M. Ramilison, P. Sadasivan, J.H. Lienhard, Surface factors influencing on flat heaters, ASME J. Heat Transfer 114 (1992) 287–290.
[4] D. Schroeder-Richter, S. Yildiz, G. Bartsch, Effect of porous coating on critical heat flux, Int. Commun. Heat Mass Transfer 23 (4) (1996) 463–471.
[5] J.Y. Chang, S.M. You, Boiling heat transfer phenomena from microporous and porous surfaces in saturated FC-72, Int. J. Heat Mass Transfer 40 (18) (1997) 4437–4447.
[6] J.Y. Chang, S.M. You, Enhanced boiling heat transfer from microporous surfaces: effects of a coating composition and method, Int. J. Heat Mass Transfer 40 (18) (1997) 4449–4466.
[7] S.G. Litter, M. Kaviany, Pool-boiling CHF enhancement by modulated porous layer coating: theory and experiment, Int. J. Heat Mass Transfer 44 (18) (2001) 4287–4311.
[8] J.T. Cieslinski, Nucleate pool boiling on porous metallic coatings, Exp. Thermal Fluid Sci. 25 (2002) 557–564.
[9] T. Kunugia et al., Ultrahigh heat transfer enhancement using nanoporous layer, Superlattices Microstruct. 35 (2004) 531–542.
[10] S. Vemuri, K.J. Kim, Pool boiling of saturated FC-72 on nanoporous surfaces, Int. Commun. Heat Mass Transfer 32 (1–2) (2005) 27–31.
[11] Y. Takata, S. Hidaka, M. Masuda, T. Ito, Pool boiling on a superhydrophilic surface, Int. J. Energy Res. 27 (2) (2003) 111–119.
[12] Y. Takata, S. Hidaka, J.M. Cao, T. Nakamura, H. Yamamoto, M. Masuda, T. Ito, Effect of surface wettability on boiling and evaporation, Energy 30 (2/4) (2005) 209–220.
[13] Y.H. Jeong, S.H. Chang, W.-P. Baek, Critical heat flux experiments on the reactor vessel wall using 2-D slice test section, Nucl. Technol. 152 (2) (2005) 162–169.
[14] W.-T. Wu, Y.-M. Yang, Enhanced boiling heat transfer by surfactant additives, in: Proceedings of Engineering Foundation Conference on Pool and External Flow Boiling, 1992, pp. 361–366.
[15] S.M. You, J.H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett. 83 (16) (2003) 3374–3376.
[16] P. Vassallo, R. Kumar, S. D'Amico, Pool boiling heat transfer experiments in silica–water nano-fluids, Int. J. Heat Mass Transfer 47 (2004) 407–411.
[17] I.C. Bang, S.H. Chang, Boiling heat transfer performance and phenomena of Al_2O_3–water nano-fluids from a plain surface in a pool, Int. J. Heat Mass Transfer 48 (2005) 2407–2419.
[18] H. Kim, J. Kim, M.H. Kim, Effect of nanoparticles on CHF enhancement in pool boiling of nano-fluids, Int. J. Heat Mass Transfer 49 (25/26) (2006) 5070–5074.
[19] S.J. Kim, I.C. Bang, J. Buongiorno, L.W. Hu, Study of pool boiling and critical heat flux enhancement in nanofluids, Bull. Polish Academy Sci. Tech. Sci. 55 (2) (2007) 211–216.
[20] T.G. Theofanous, T.N. Dinh, J.P. Tu, A.T. Dinh, The boiling crisis phenomenon – Part II: Dryout dynamics and burnout, Exp. Thermal Fluid Sci. 26 (6/7) (2002) 793–810.
[21] D.Y. Kwok, A.W. Neumann, Contact angle interpretation in terms of solid surface tension, Colloids Surf. 161 (1) (2000) 31–48.
[22] N. Zuber, Hydrodynamic aspects of Boiling Heat Transfer, Thesis, Univ. of California, LA, 1959.
[23] S.G. Kandlikar, A theoretical model to predict pool boiling CHF incorporating effects of contact angle and orientation, J. Heat Transfer 123 (2001) 1071–1079.