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تأثير معدل ترسب الجسيمات متناهية الصغر على تدفق الحرارة الحرجة في غليان بركة

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الخلاصة

يتم دراسة التدفق الحراري الحرج تجريبيا للمياه وسوائل نانو (T_iO_2) في غليان بركة. أجريت التجارب مع (Ni-Cr) سلك التسخين ذو قطر 0.28 مم. يتميز ترسب الجسيمات متناهية الصغر في سلك سخان تدفق الحرارة المستمر من خلال تغيير تركيزات حجم نانو السائل (0.01 و ٪0.05)، ووقت الغليان (1 to 16 دقيقة). وأشارت النتائج إلى أن تدفق الحرارة الحرجة قد تعزز مع زيادة ترسب الجسيمات على سلك سخان مقارنة مع الأسلاك العارية. تم تعزيز تدفق الحرارة الحرجة لتصل إلى ٪93 عندما ترسب الجسيمات لمدة 16 دقيقة. وأشارت قياسات البلل الى أن زاوية الاتصال تنخفض مع زيادة في معدل الترسيب.

Effect of nanoparticle deposition rate on critical heat flux in pool boiling

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ABSTRACT

Critical Heat Flux (CHF) is experimentally investigated for water and TiO_2 nanofluids in pool boiling. Experiments were carried out with Ni-Cr heating wire of 0.28 mm diameter. The nanoparticle deposition in the constant heat flux heater wire is characterized by varying the nanofluid volume concentrations (0.01 and 0.05 %) and boiling time (1 to 16 minutes). Results indicated that CHF was enhanced with increased particle deposition on heater wire compared to the bare wire. The CHF got enhanced up to 93% when the particle deposition occurred for 16 minutes. Wettability measurements indicated that the contact angle decreases with the increase in the deposition rate.

Keywords: Critical heat flux; nanofluids; pool boiling; nanoparticle deposition; boiling time.

Nomenclature

q'' – Critical heat flux (kW/m^2)

V_{max} – Maximum voltage (V)

I_{max} – Maximum current (A)

q''_z – Critical heat flux by Zuber's correlation (kW/m^2)

g – Acceleration due to gravity (m/s^2)

L – Length of wire (m)

Φ_v – Volume concentration of nanofluid

Φ_m – Mass fraction of nanoparticles

ρ_f – Density of base fluid

ρ_p – Density of nanoparticles

h_{fg} – Latent heat of vaporization (kJ/kg)

ρ_l – Density of liquid

ρ_g – Density of vapor

σ – Surface tension (N/m).

1. INTRODUCTION

Nucleate boiling is an effective mode of heat transfer, where high heat flux is extracted from surfaces. This mode is utilized in numerous applications such as nuclear/thermal reactors, electronic devices, and cryogenics. Depending on the value of the CHF, the heat transfer shifts from nucleate boiling to film boiling. The latter is not an effective mode of heat transfer across the heater surfaces, thus causing a drastic increase in the temperature of the heated surface, which leads to physical destruction and a catastrophe. Thus, it becomes essential to understand the CHF that enables the designers to improve the safety parameters and to operate the appliances at higher temperatures. In recent past, nanofluids are being treated as effectual heat transfer fluids to enhance the CHF at pool boiling temperatures. It is observed from the literature that a low volume percentage addition (< 0.1) of nanoparticles to the base fluid can appreciably improve the CHF without significant changes in physical properties (You *et al.* 2003). Thus, in the present study, nanoparticles are added to the base fluid, and their effect in the enhancement of the CHF is investigated. The following section discusses the literature pertaining to CHF of nanofluids with water as the base fluid.

Numerous researchers have investigated the critical heat flux characteristics of pool boiling nanofluids. You *et al.* (2003) experimentally investigated the boiling curve on a polished copper flat square plate heater to estimate critical heat flux in pool boiling. Al_2O_3 nanofluids of volume fraction ranging from 0.001 to 0.05g/L are considered. CHF was found to be enhanced up to 200% in the nucleate boiling regime. Taylor and Phelan (2009) presented a review related to pool boiling of nanofluids. It is observed that surface modification is one of the critical parameters affecting the boiling phenomena, which enhances the heat transfer by 25 to 40% in nucleate boiling. HD Kim *et al.* (2007) conducted experiments to investigate the CHF with different concentrations of TiO_2 and Al_2O_3 nanoparticles in water. The concentration ranged from 0.00001 to 0.1% by volume. A Ni-Cr wire of 0.2 mm diameter was used to find the CHF, and a 100% increase with an increase in the volumetric concentration of nanoparticles was reported. Further, they observed the nanoparticles deposition on heater surface during pool boiling.

The critical heat flux estimated using nanoparticle deposited heater wire in water was similar to that of bare heater wire (without deposition) in nanofluids. This led to the concluding fact that deposition of nanoparticles on the heater surface modifies the critical heat flux significantly. SJ Kim *et al.* (2007) experimentally investigated the boiling heat transfer and critical heat flux using alumina, silica, and zirconia nanoparticles in water. Test was conducted using 316-grade stainless steel heater wire of 0.318 mm diameter. The concentrations of nanoparticles in the water considered are 0.001, 0.01, and 0.1% by volume. Enhancement in critical heat flux was found to be up to 52, 75, and 80% for alumina, zirconia, and silica nanofluids, respectively. They concluded that the CHF enhancement was due to the porous layer of nanoparticles formed on heater surface resulting in the improvement of wettability of heater surface. Kandlikar (2001) developed a theoretical model to predict the CHF in pool boiling considering the effect of contact angle and orientation of heater wire in water, refrigerants, and cryogenic liquids. The model predicts well for heater surface orienting from horizontal (0^o) to vertical (90^o). In case of subcooling, the model gets valid only for flat surfaces. Hsu and Chen (2012) studied the wettability effect due to deposition of silica nanoparticles of size 40 nm on the heater surface in pool boiling. A copper block of cross-section

15cm × 15cm was used to make super hydrophilic surfaces. They reported that bubble formation on super hydrophilic surface was relatively smaller than that on the hydrophobic surface at 100°C. Surface wettability of heater surface influences the bubble growth when surface temperature was at 100°C. When the surface contact angle is large (~150°), heat transfer from the heater surface to the liquid is obstructed due to larger bubbles, thus resulting in decrement of critical heat flux. Kim *et al.* (2013) investigated the effect of nanoparticles on boiling heat transfer coefficient and critical heat flux. Nanofluids were prepared with using Al_2O_3 nanoparticles of size 40-50 nm in pure water. The test was conducted on 0.2 mm Ni-Cr heater wire with concentrations of nanoparticles of 0.00001, 0.0001, 0.001, 0.01, and 0.1% by volume. The maximum enhancement in critical heat flux was 103% at 0.001% compared to pure water, beyond which the critical heat flux started to diminish gradually. Also, they observed that the boiling heat transfer coefficient increased with heat flux, while it decreased as the nanoparticles concentration increased under the same heat flux. It was observed that the boiling heat transfer coefficient and critical heat flux depend on the nanoparticles deposition on the surface and number of active cavities formed during the deposition.

Golubovic *et al.* (2009) investigated the critical heat flux in pool boiling with varying types, concentrations, and particle size of nanoparticles. The nanoparticles used for experiment were alumina oxide (Al_2O_3) of particle size 46 and 22.6 nm and bismuth oxide (BiO_2) of particle size 38 nm. The critical heat flux test was conducted for particle concentration ranging from 0.001 to 0.008 g/l in steps of 0.001. The CHF was seen to increase with particle concentration up to a limit beyond which the CHF increment was insignificant. The maximum heat flux enhancement was 150 and 133% in alumina oxide and bismuth oxide, respectively. The effect of particle size of nanoparticles was observed to be negligible in enhancement of critical heat flux. In addition to the deposition of nanoparticles on heater surface, it also decreases the static surface contact angle, which is considered as the primary reason for enhancing the CHF.

Park *et al.* (2014) carried out experiments to investigate the effect of heater deposition layer on CHF. They used alumina nanofluids of 0.01% volume concentration with particle size 50 nm. Experiments were conducted on Ni-Cr heater wire of 0.4868 mm diameter at different boiling time and constant heat flux. The deposition of nanoparticles on the heater surface was observed to be different with boiling time. The results indicated that the CHF values got enhanced by 120% up to the boiling time of 10 minutes and thereafter started decreasing. Wettability and hydrodynamic instability were considered to be the reason for enhancement of CHF during initial boiling times (< 10 minutes), and the decrease in porosity of the deposition layer on heater surface resulted in decrement of CHF at the latter boiling times. The same authors investigated the effect of nanoparticle deposition on heater surface based on hydrodynamic instability model (Park and Bang, 2014). Experiments were conducted for different nanofluids of 0.01% volume concentration of ZnO, SiO_2, SiC, Al_2O_3, graphene oxide, and CuO nanoparticles in distilled water and R-123. Critical heat flux test was carried out on Ni-Cr wire of 0.49 mm diameter and 55 mm length. The CHF value for each nanofluid is compared with measured Rayleigh–Taylor wavelength. The largest enhancement was 160% with CuO and the lowest was 90% with ZnO nanofluids. Interestingly, it is observed that the nanoparticle deposition on heater surface introduces Rayleigh–Taylor instability wave of different wavelengths, which, in turn, influences the bubble diameter and, thus, establishes a correlation for the CHF in terms of Rayleigh–Taylor wavelength. Chouarfa *et al.* (2014) numerically studied the heat transfer in partial nucleate boiling and developed a mathematical model based on experimental data from literature, which can be further extended to a fully developed nucleate boiling with minor corrections. The model considered temperature difference between walls, saturation temperature of liquid, physical properties of liquid and vapor, and density of nucleation sites. The correlation is accurate within 15% of the considered experimental data results.

It is observed from the above literature that a huge number of articles exist in the field of critical heat flux. Numerous works on CHF in nanofluids have been investigated, considering different nanoparticles of various sizes. Interestingly, it was noted from the literature that the CHF values got enhanced with the deposition of nanoparticles on the heater surface. For instance, the work of Kim *et al.* (2014) indicates that CHF increases with the increase in nanoparticles deposition. Also the nanoparticle deposition can be controlled using the boiling time and heat flux to the heater. Further, the authors observed that not much literature or very few were found in the deposition rate of nanoparticles with boiling time (Park *et al.*, 2014). To understand the deposition rate, the present study experimentally investigates the effect of boiling time for nanoparticle deposition and its effect on CHF enhancement. A thin wire of 0.28mm diameter is considered for the study, which is supplied with constant heat flux in pool boiling of nanofluids. To investigate the role of boiling time on deposition, experiments are conducted using TiO_2 nanoparticles with double distilled water. The CHF tests are carried out using deposited wire in pool boiling of double distilled water, and the enhancement in CHF value is compared with that of the bare wire. Further, the CHF variation with respect to the boiling time is discussed.

2. EXPERIMENTAL SETUP AND PROCEDURE

Schematic of the experimental apparatus for CHF test is shown in Figure 1. The boiling container is of two liters capacity and is made of borosilicate glass of 130 mm diameter and 195 mm length. One kW plate heater with temperature controller is used for heating the fluid up to saturation temperature. A Platinum100 RTD three-wire sensor connected with temperature indicator is used to measure the bulk temperature of test fluid. Dimmer-stat and Rheostat are used to vary coarse and fine step power supply of test heater, respectively. A digital voltmeter and ammeter with current transformer of 10:1 ratio is installed in the control panel to measure the voltage and current in the test heater during the CHF test. The top lid of the boiling container is designed to accommodate copper electrode, PT-100 RTD sensor, and reflux condenser. The reflux condenser is used to condense the bulk vapor produced during boiling and maintain the atmosphere pressure within the boiler. CHF experiments are conducted through Joule heating method using Ni-Cr heater wire of 0.28 mm diameter. Both ends of Ni-Cr wire are fixed to copper electrode using mechanical clamp.

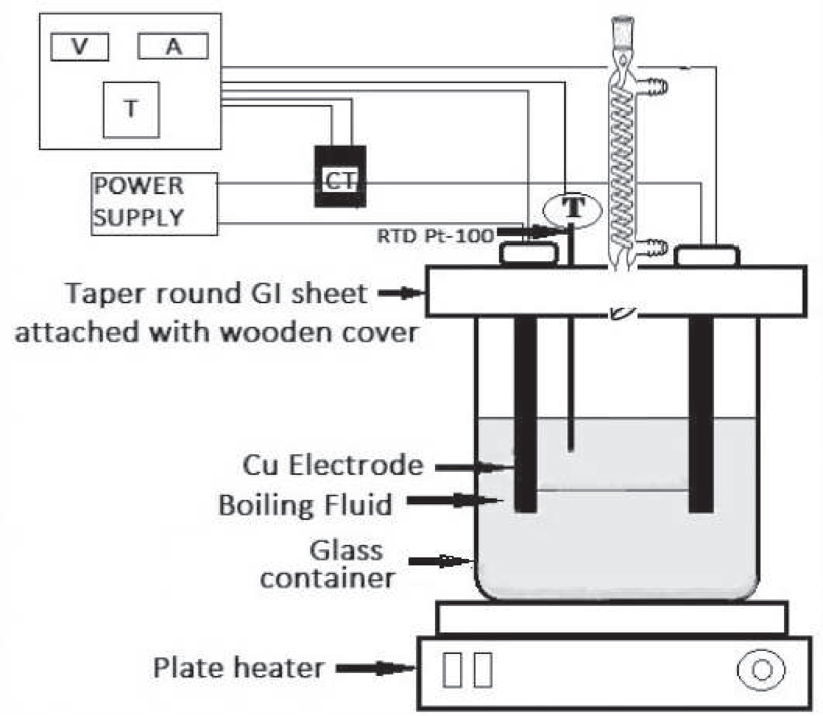

Figure 1: Schematic diagram of experimental setup.

Nanofluids are prepared by double-step method using commercially available TiO_2 nanoparticles of 10- 30 nm size at volume concentrations of 0.01, 0.05, and 0.1%. Initially, experiments are carried out with the above three volume concentrations in order to compare the CHF enhancements with those of the literature (Kim *et al.*, 2014). Also, it is noted from the literature that the CHF enhancement is significant in the volume concentration range of 0.01 to 0.1% compared to the lower volume concentration range of 0.00001 to 0.001 % for TiO_2 nanofluids (Kim *et. al.*, 2014), thus utilizing the former volume concentration values for the present investigation.

Volume concentration of nanofluids is determined by Eq. (1) as mentioned by Bang and Chang (2005).

$$\emptyset_v = \left[\left(\frac{1-\emptyset_m}{\emptyset_m}\right)\frac{\rho_p}{\rho_f} + 1\right]^{-1} \tag{1}$$

Figure 2 shows Scanning Electron Microscope (SEM) image of the dry TiO_2 nanoparticles. Initially, nanoparticles are weighted using electronic balance, then dispersed in double distilled water. In order to ensure stability and uniformity of dispersed nanoparticle in the base fluid, ultrasonication was performed for three hours before conducting experiments.

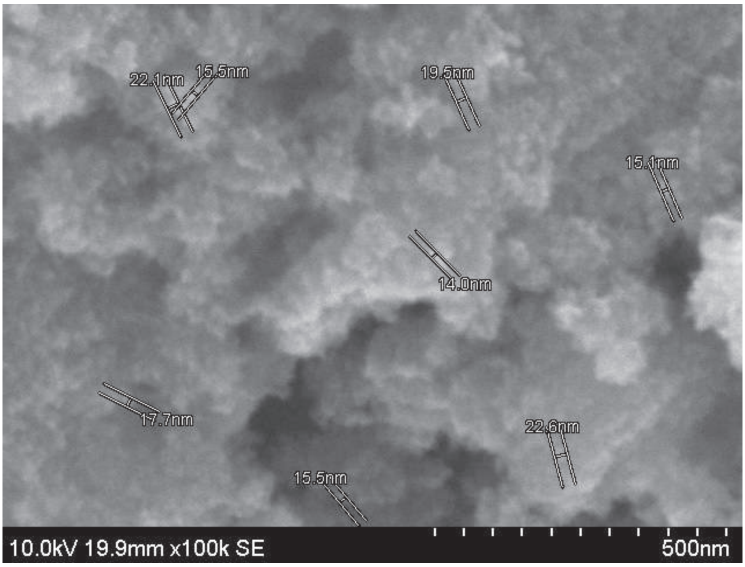

Figure 2: SEM image of dry powdered TiO_2 nanoparticles indicating its size ranging from 10 to 30 nm.

In the present study, since the nanoparticles added are in low volume percentage, the boiling point of nanofluids is assumed to be the same as that of the base fluids. However, the literature reports such variation within ± 1^{o} C (HD Kim *et al.*, 2007; Das *et al.* 2003). Precautions are taken to ensure cleanliness of conducting the experiments. The glass container is cleaned using acetone and water after each experiment, and fresh nanofluids are used for every observation to maintain the uniformity throughout the experiments. The test fluid is heated up to a saturation temperature using auxiliary plate heater, and fluid temperature is measured using a PT-100 RTD sensor. The reflux condenser placed on the top lid of glass container ensures vapor condensation and thus maintains the constant volume concentration of boiling fluid throughout the experiments. CHF tests are conducted after stabilizing the bulk temperature of test fluid at saturation temperature (98^{o}C – 99^{o}C). To determine the CHF, the heat flux input to the test wire heater is periodically increased with time steps. Nearing to the CHF, the increment in the heat flux is further slowed down with time steps, and the value at which the heater wire ruptures is noted down. Similar tests are carried out to meet the objective of this paper. The CHF is calculated using Eq. (2).

$$q'' = \frac{V_{max}\, I_{max}}{\pi D L} \tag{2}$$

The experimental uncertainty in the estimated value of critical heat flux is determined using the Kline and McClintock method (Holman, 2001). The error in the voltage measurements is within ± 1.2% of full scale, current measurements are within ± 0.5% of full scale, and length of wire is within ± 1mm. The error in the temperature measurements is ± 1^{o} maximum. The uncertainties estimated for CHF are within ± 4.32%. The uncertainty of contact angle measurements is ±2°.

3. RESULTS AND DISCUSSION

The experimental test rig is validated by conducting a number of trial experiments to determine

CHF using a bare Ni-Cr wire of 0.28 mm diameter in double distilled water. The mean CHF values are compared with the most widely accepted Zuber's correlation, Eq. (3), for boiling on an infinite, upward facing horizontal surface (Zuber, 1959).

$$q_z'' = \frac{\pi}{24}\rho_g^{0.5}h_{fg}\left[\sigma g\left(\rho_l-\rho_g\right)\right]^{\frac{1}{4}} \tag{3}$$

The measured average value of CHF is found to be 907 kW/m^2. However, this value is 17.5% lower than that of the estimated value using Zuber's correlation, Eq. (3), since the correlation corresponds to an infinite horizontal plate and not to a wire as discussed by Barkhru and Lienhard (1972). The present CHF value is in good agreement with Kim *et al.* (2007; 2014) where they conducted studies with Ni-Cr wire of diameter 0.2 mm. The following section illustrates the enhancement in CHF using nanofluids.

3.1 The CHF of nanofluids

In the present section, CHF tests were conducted with bare Ni-Cr wire heater in TiO_2 nanofluids with volume concentrations of 0.01, 0.05, and 0.1%. The critical heat flux variation with volume concentrations is shown in Figure 3. The figure shows the enhancement in the CHF using nanofluids compared to the pure water as base fluid. Further, CHF increases with the nanoparticles volume concentration. The CHF value found using pure water is lesser than that of Zuber's correlation due to the reason explained in the previous section.

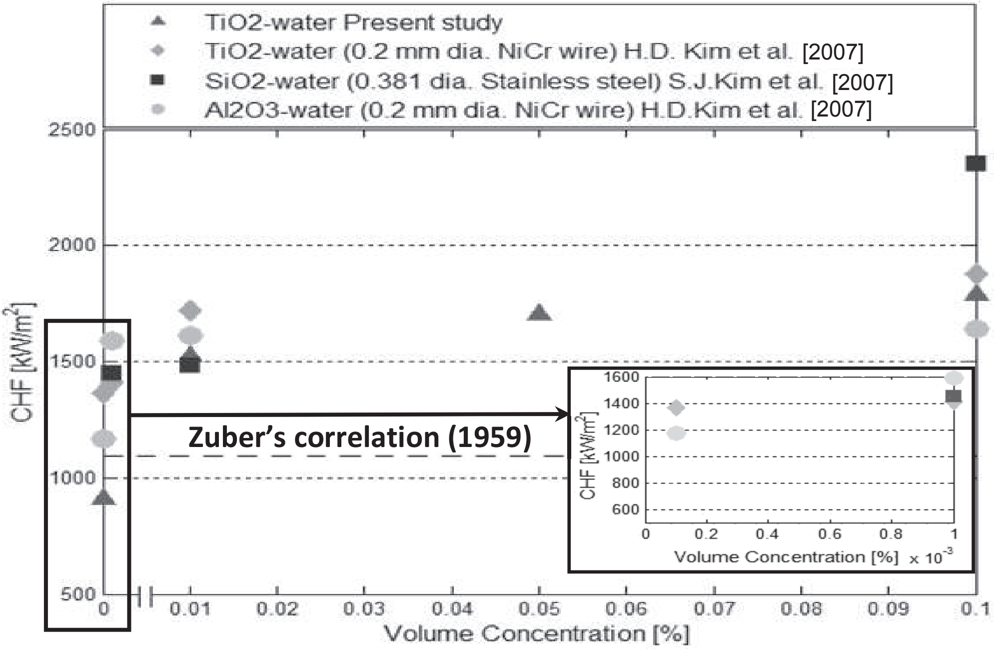

Figure 3: CHF enhancement using nanofluids for various volume concentrations. The values at the lowest volume concentration are enlarged and shown as an inset.

The increase rate of CHF with volume concentration is very significant, up to 0.05%, beyond which the increasing rate is moderate. These results are in congruence with those of You *et al.* (2003) and Kim & Kim (2009), where their experimental critical heat flux continuously increased up to a certain concentration. Figure 3 also shows a comparison between the present experimental results and those of Kim *et al.* (2007), and similar trends are observed. The maximum enhancement in CHF with nanofluids is found to be 900 kW/m^2 approximately, which is similar to the literature. Figure 4 shows the comparison between percentages of CHF enhanced using nanofluids and the past literature. At 0.1% volume concentration, the CHF enhancement compared to pure water is approximately 97%. CHF is enhanced by 88 and 67% for volume concentrations of 0.05 and 0.01%, respectively.

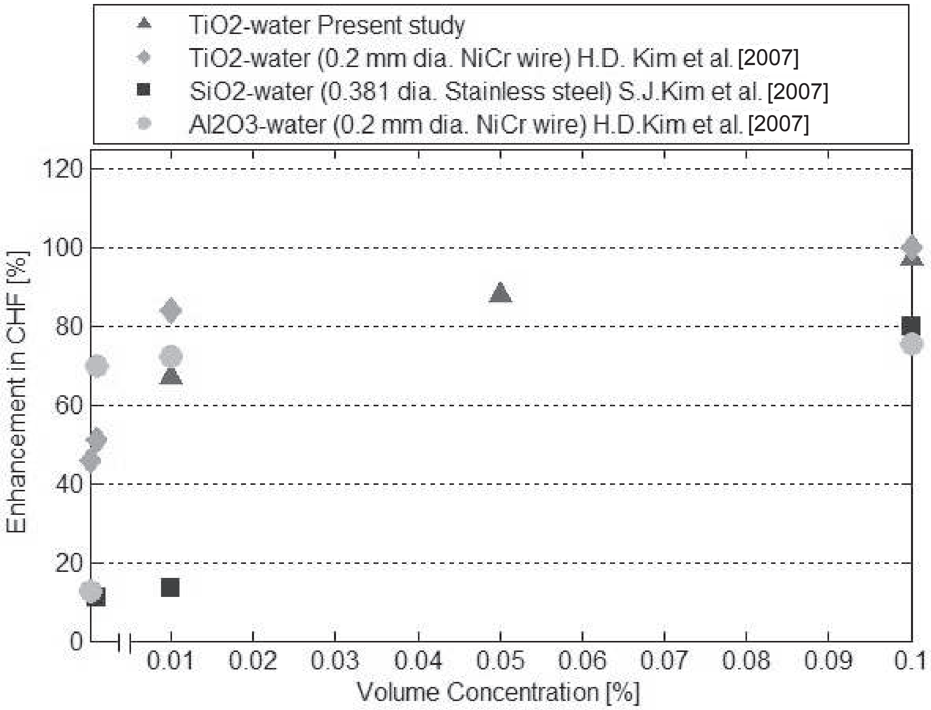

Figure 4: CHF percentage enhancement using nanofluids.

3.2 Nanoparticles deposition on heater surface

The procedure followed for preparation of nanoparticle coated heater surface similar to the CHF tests conducted in previous sections in nanofluids. However, here, the test heater is subjected to a constant heat flux of 360 kW/m^2 for different boiling times at volume concentrations of 0.01 and 0.05%. The boiling times varied from 1 to 16 minutes using Ni-Cr wire of 0.28 mm diameter as test heater. Initially, tests are conducted with wire heater in nanofluids without heating, and then heat was supplied to the heater to confirm the effect of nucleation, growth, and departure of vapor bubbles on coating. It is observed that the wire heater, without heat supply, produced negligible deposition/coating on heater surface. This indicates that deposition in heaters happens due to nucleation growth and not due to nanoparticle sedimentation. The nanoparticle deposited heater surfaces are examined using Scanning Electron Microscopy (SEM) for clear visualizations of coating and to observe the characteristics of heater surface. Figure 5 shows the SEM images of the bare heater wire without nanoparticle deposition at magnification factor of 250X and 1000X that indicates the evenness in the heater surface. This figure will be used for the comparison with those of wire heater deposited with nanoparticles.

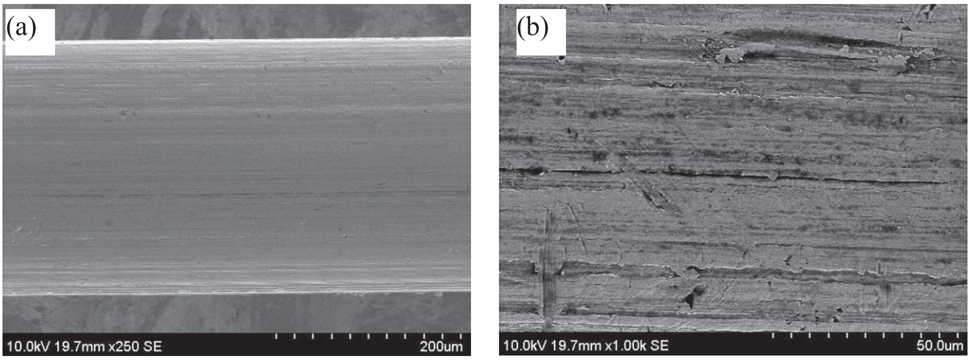

Figure 5: SEM images of bare Ni-Cr wire at magnification factors (a) 250X and (b) 1000X.

Figure 6 shows the SEM images of heater surface after for different boiling times for volume concentrations 0.01% and 0.05%. It is evident from the figures that the deposition of nanoparticles on the heater surface increases with boiling time (Kim *et al.*, 2014; Vassallo *et al.*, 2004; Sharma *et al.*, 2013). However, the rate of deposition is seen to be higher at boiling times of 2 to 8 minutes. In comparison to the bare wire, it is understood that the nanoparticles deposition reconfigures the microscopic structure of the heater surface. At this point, it is worth mentioning that the amount of deposition on the heater wire could not be quantified at various boiling times. Thus, during the CHF tests, instead of quantifying the CHF in terms of deposition parameter, they are indirectly represented as the function of boiling times.

3.3 CHF tests with nanoparticles deposited heater

The CHF tests using nanoparticles deposited heater are carried out in double distilled water as the test fluid in pool boiling conditions. Precautions are taken to avoid wearing out the nanoparticles from wire heater while conducting CHF tests. Figure 7 shows the CHF results variation with boiling time for deposited wire and shows the comparison with bare wire and Zuber’s correlation. Approximately 80% enhancement in CHF was observed for 4 minutes boiling time, followed by 88 and 93% for 8 and 16 minutes, respectively. Hence, it can be concluded that the nanoparticles deposition has larger influence on CHF compared to the bare wire, and moreover the influence is much larger at relatively lower boiling times. The rate of increment of CHF with boiling time is rapid up to 8 minutes and thereafter becomes moderate. This also indicates the fact that the CHF is significantly enhanced up to a certain value of nanoparticles deposition, beyond which the rate of deposition is immaterial. Further, the effect of volumetric concentration on CHF is significant at lower boiling times (≤ 8 minutes), while it is insignificant at higher boiling times.

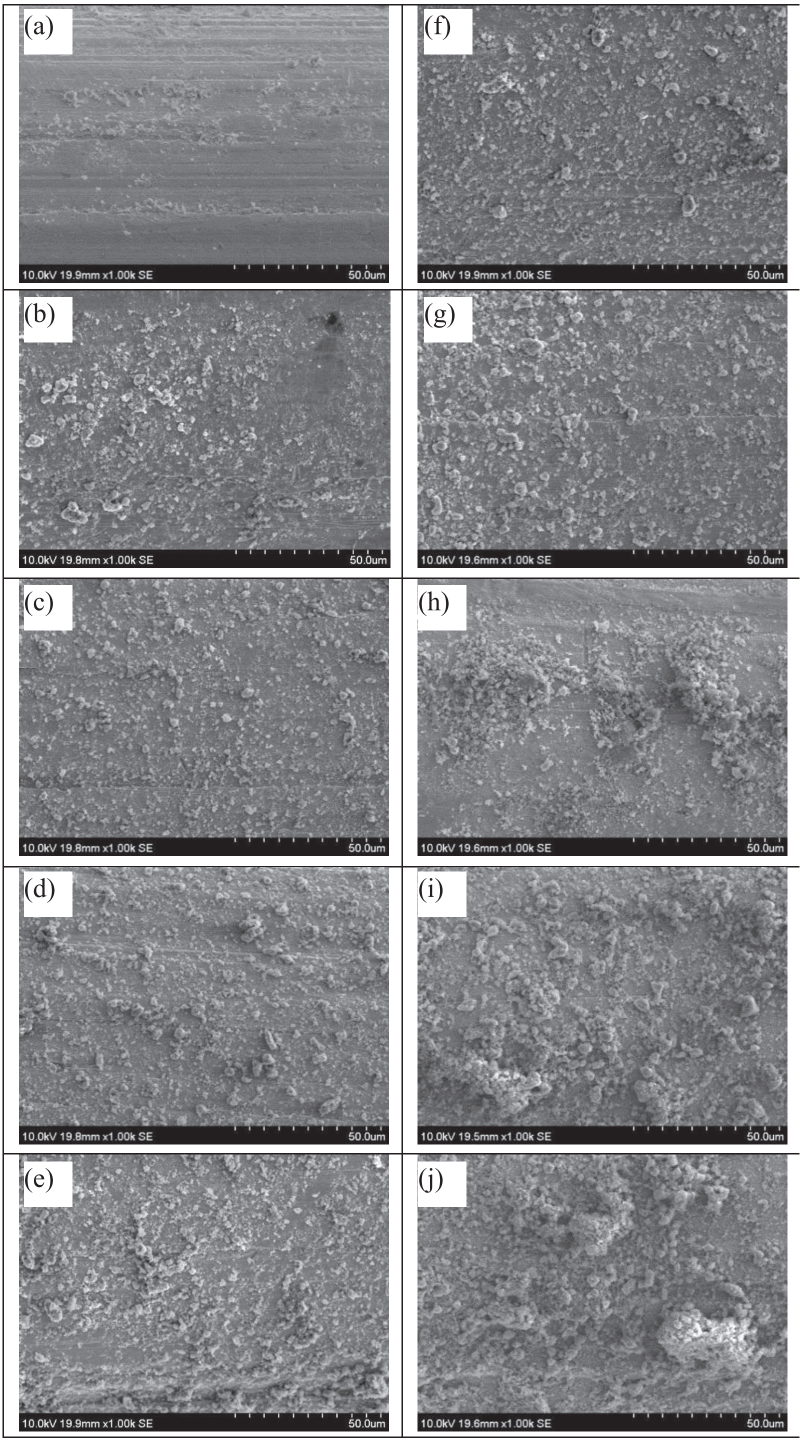

Figure 6: SEM images of nanoparticles deposited in Ni-Cr test wire heater for different boiling times of 1 minute (a, f); 2 minutes (b, g); 4 minutes (c, h); 8 minutes (d, i); and 16 minutes (e, j) at volume concentrations of 0.01% (a-e) and 0.05% (f-j) at magnification factor of 1000X.

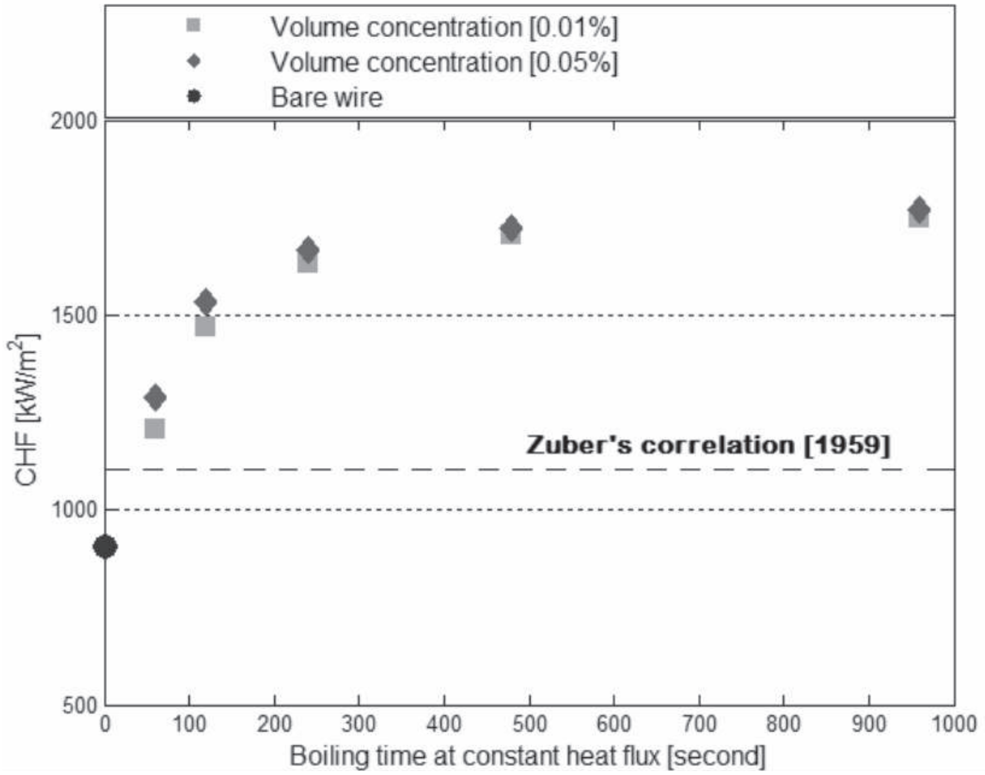

Figure 7: CHF values measured for test wire heater deposited with nanoparticles at different boiling times.

Figure 8 depicts the CHF ratio (ratio of CHF with deposited wire to CHF using bare wire) with boiling time for two different volume concentrations of 0.01 and 0.05%. The maximum enhancements in CHF are 93 and 95 % at boiling time of 16 minutes for volume concentrations of 0.01% and 0.05%, respectively. The CHF ratio gradually increased up to a boiling time of 8 minutes, beyond which the ratios are almost constant. The CHF ratios obtained from the present study are compared with those of Park *et al.* (2014), as shown in Figure 8. The enhancement ratios of CHF in the current study are lower by 17% compared to those of Park *et al.* (2014), which could be due to the difference in the experimental parameter, such as heater size and supplied heat flux, and types of nanoparticles.

3.4 Wettability characteristics

Numerous researchers have discussed the various parameters like surface roughness, porosity, wettability, and capillary wicking performance of heater surface to understand the mechanism behind CHF enhancement using nanofluids. In the present study, improved wettability characteristics of nanoparticle deposited heater surface are considered as one of the mechanisms behind the CHF enhancement.

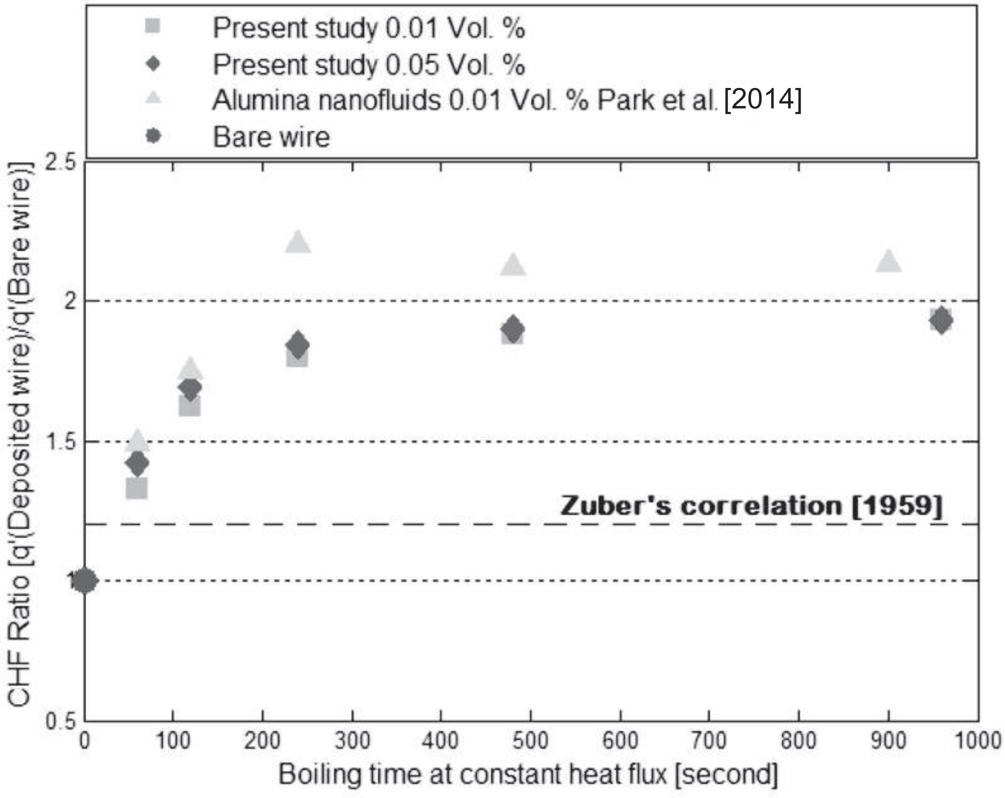

Figure 8: CHF ratio of nanoparticles deposited wire for different boiling times.

Contact angle of water droplet characterizes the surface wettability (Kim *et al.* 2014). In order to measure the contact angle, a 5µl double distilled water drop is generated on bare and nanoparticle deposited wire surfaces at atmospheric temperature and pressure. The high resolution magnified images are captured as shown in Figure 9. A tangent is drawn to the edge of the droplet image, and the angles are measured with the horizontal as shown in Figure 9. The contact angles are measured at three different positions for each heater surface and averaged. Figure 10 represents the results of measured contact angles on bare wire and nanoparticles deposited wire for different boiling times. The test with bare wire gave contact angle of around 70° and that measured at one minute boiling time is around 50° and thereafter decreased with the boiling time. The decrement is more significant up to 8 minutes and moderate, thereafter, indicating that the wettability of heater surface was insignificant beyond a certain deposition rate.

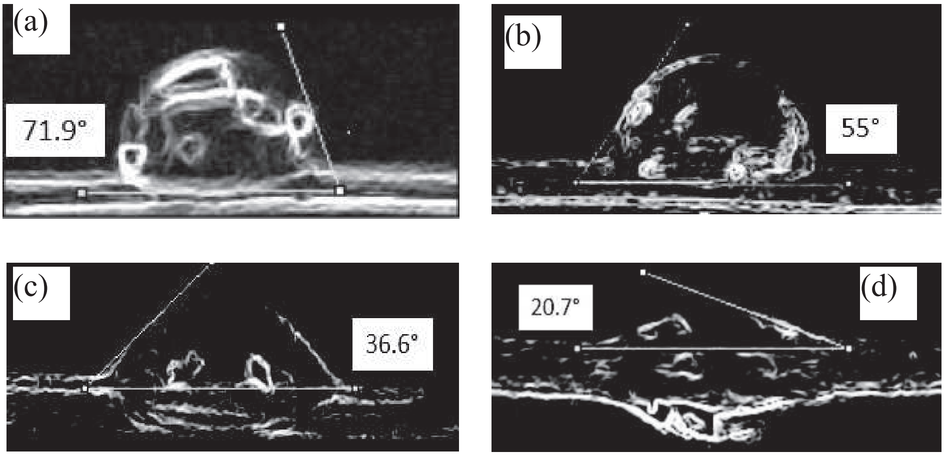

Figure 9: Contact angle measurements of droplet on a Ni-Cr wire heater surface of (a) bare wire (b) for 1 minute deposition at 0.01% vol. concentration, (c) for 4 minute deposition at 0.05% vol. concentration, and (d) for 16 minute deposition at 0.05 % vol. concentration.

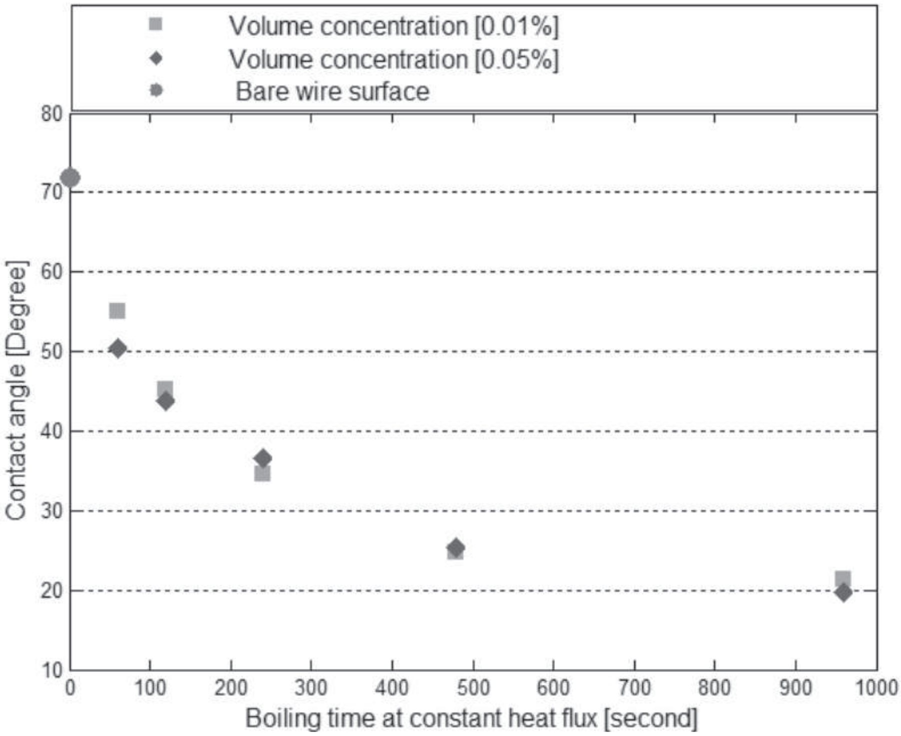

Figure 10: Static contact angles of nanoparticle deposited wire for different boiling times.

4. CONCLUSIONS

An experimental investigation is carried out to understand the effect of deposition rate on CHF in pool boiling. Ni-Cr wire of 0.28 mm diameter is considered as heater, and TiO_2 with water is considered as nanofluid. Preliminary tests' results indicate that CHF of nanofluids increases with volume concentration of nanoparticles. The CHF enhancement is found to be 67, 88, and 97% for volume concentrations of 0.01, 0.05, and 0.1%, respectively.

The heater surface is deposited by nanoparticles using Joule's heating method by maintaining the heater at constant heat flux at saturated temperature under atmospheric pressure. Various deposition surfaces are obtained for boiling times ranging from 1 to 16 minutes with nanofluids volume concentrations of 0.01 and 0.05%. The deposition of nanoparticles on the heater surface strongly depends on boiling time, which is verified by SEM images. Results conclude the fact that the CHF got significantly enhanced up to a certain value of nanoparticle deposition, beyond which the rate of deposition is immaterial. Approximately 80, 88, and 93% enhancement in CHF were observed for deposition up to 4, 8, and 16 minutes, respectively. Results conclude that the rate of deposition of nanoparticles is found to be higher for boiling time up to 8 minutes and is comparatively lower beyond 8 minutes and above. Wettability results concluded that the larger the deposition or boiling time, the lower the contact angle leading to higher critical heat flux.

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