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Boiling induced nanoparticle coating and its effect on pool boiling heat transfer on a vertical cylindrical surface using CuO nanofluids

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Abstract Experiments were performed to study boiling induced nanoparticle coating and its influence on pool boiling heat transfer using low concentrations of CuO-nanofluid in distilled water at atmospheric pressure. To investigate the effect of the nanoparticle coated surface on pool boiling performance, two different concentrations of CuO nanofluids (0.1 and 0.5 g/l) were chosen and tests were conducted on a clean heater surface in nanofluid and nanoparticle coated surface in pure water. For the bare heater tested in CuO nanofluid, CHF was enhanced by 35.83 and 41.68 % respectively at 0.1 and 0.5 g/l concentration of nanofluid. For the nanoparticle coated heater surface obtained by boiling induced coating using 0.1 and 0.5 g/l concentration of nanofluid and tested in pure water, CHF was enhanced by 29.38 and 37.53 % respectively. Based on the experimental investigations it can be concluded that nanoparticle coating can also be a potential substitute for enhancing the heat transfer in pure water. Transient behaviour of nanofluid was studied by keeping heat flux constant at 1,000 and 1,500 kW/m^2 for 90 min in 0.5 g/l concentration. The boiling curve shifted to the right indicating degradation in boiling heat transfer due to prolonged exposure of heater surface to nanofluid. Experimental outcome indicated that pool boiling performance of nanofluid could be a strong function of time and applied heat flux. The longer the duration of exposure of the heater surface, the higher will be the degradation in heat transfer.

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List of symbols

A Surface area of the heater (m^2)
C_p Specific heat capacity (J/kg K)
F Pressure correction factor
g Gravitational acceleration (m s^{-2})
h Heat transfer coefficient (W/m^2 K)
h_{fg} Latent heat (J kg^{-1})
I Current (A)
L Length (m)
M Molecular weight
p Pressure (Pa)
q Heat flux (W/m^2)
Rp Surface roughness (μm)
T Temperature (K)
U Uncertainty
V Voltage (V)
w Weight concentration (g/l),wall
W Power (W)

Greek symbols

ρ Density (kg m^{-3})
σ Surface tension (N m^{-1})
μ Viscosity (Pa s)

Subscripts

c Critical
HF Heat flux
f Fluid
fg Vaporization
m Mass

max	Maximum
nb	Nucleate boiling
nf	Nanofluid
o	Reference
p	Particle
r	Reduced
s	Surface
f	Liquid
v	Vapour

1 Introduction

With increasing heat transfer rate of the heat exchange equipment, conventional process fluids with low thermal conductivity can no longer will meet the requirements of high-intensity heat transfer. For the development of compact heat exchangers with higher effectiveness, low thermal property of heat transfer fluids is a primary limitation. An effective way of improving the thermal conductivity of fluids is to suspend small solid particles, metallic or non metallic, in fluids like water, ethylene glycol etc. [1]. Traditionally, solid particles of micrometer or millimeter magnitudes were mixed in the base liquid. Although the solid additives may improve heat transfer coefficient, practical uses are limited because, the micrometer and/or millimeter-sized particles settle rapidly, clog flow channels, erode pipelines and cause severe pressure drops. The concept of nanofluids refers to a new kind of heat transport fluids in which nano scaled metallic or nonmetallic particles are suspended in base fluids. Many experimental investigations have revealed remarkably higher thermal conductivities of nanofluids than those of conventional pure fluids and have pointed out their potential as substitute fluids for heat transfer enhancement. Since nanoparticles used with a base fluid like water incur little or no penalty in pressure drop and behave like a pure fluid, research focus was shifted from thermal characterization of nanofluids to heat transfer enhancement. Heat transfer enhancement studies included from convection problems to phase change problems covering surface characterization, wettability studies etc.

Initial studies on pool boiling were mainly concerned with boiling heat transfer coefficients and critical heat flux (CHF) values. You et al. [2] and Vassallo et al. [3] showed that boiling heat transfer was unaffected but CHF increased significantly using nanofluids. Kim et al. [4] investigated role of nanoparticle deposition and surface wetting characteristics by measuring the static contact angle over the heater surface. Das et al. [5] studied the role of surface roughness, particle size and nanoparticle concentration on nucleate boiling heat transfer. Sefiane [6] explained the CHF enhancement due to structural disjoining pressure and contact pinning. Kim et al. [7] reported in their experimental findings about the modification of heater surface due to nanoparticle coating which resulted in CHF enhancement by 160 %. Studies have also been carried out on the heat transfer coefficient of nanofluids in natural and forced flow [8–11]. Nanoparticles in nanofluids can play a vital role in two-phase heat transfer systems as evident from some of the recent studies on pool boiling [12, 13, 15, 16]. Lotfi et al. [12] investigated boiling heat transfer and quenching capabilities on a silver sphere of 10 mm diameter at 700 °C immersing it in TiO_2 nanofluid at 90 °C. They found lower film boiling heat flux in the TiO_2 nanofluid compared with water. The accumulation of nanoparticles at the liquid–vapor interface was found to reduce the vapor removal rate from the film, creating a thick vapor film barrier which reduced the minimum film boiling heat flux.

Huang et al. [13] conducted series of experiments using TiO_2 nanoparticle-coated nickel wires of various nanofluid concentrations ranging from 0.01 to 1 wt. % with various processing heat fluxes from 0 to 1,000 kW/m^2. The experimental results demonstrated up to 82.7 % enhancement on critical heat flux for coated nickel wire processed in 1 wt. % concentration, with 1,000 kW/m^2 boiling in pure water. By measuring the contact angle, they revealed that the hydrophilic porous coating formed by vigorous vaporization of TiO_2 nanofluid in nucleate boiling regime enormously modified the wettability of heating surface consequently improving the CHF.

Park et al. [14] performed quenching experiments with copper spheres in alumina nanoparticles using 5–20 % by volume concentration and liquid sub cooling from 20 to 80 K. Their results indicated film boiling heat transfer in nanofluids was lower than in pure water. However they reported that after the quenching test, the unwashed sphere quenched more rapidly apparently bypassing the film boiling mode.

Stutz et al. [15] studied the effects of nanostructured surface coatings on boiling heat transfer and CHF by performing boiling experiments on a 100 μm diameter platinum wire immersed in saturated water or pentane at 1 bar. They obtained nanostructured surface coating by the deposition of charged γ-Fe_2O_3 nanoparticles (average diameter of 10 nm) on the platinum wire. Two different processes were compared: vigorous boiling and electrophoresis. They found deposition of nanoparticles onto the heated surface induced a significant increase of the boiling critical heat flux (CHF) and increase of wettability. It also induced a decrease of the heat transfer coefficient when the wire was entirely covered with nanoparticles. They concluded that critical heat flux enhancement depends on the wettability of the fluid compared with the bare heater.

Phan et al. [16] investigated the influence of surface wettability on nucleate boiling heat transfer. Nano coating techniques were used to vary the water contact angle from 20° to 110° by modifying nano scale surface topography and chemistry. The bubble growth was recorded by a high speed video camera to enable a better understanding of the surface wettability effects on nucleation mechanism. For hydrophilic (wetted) surfaces, it was found that a greater surface wettability increases the vapour bubble departure radius and reduces the bubble emission frequency. Moreover, lower superheat is required for the initial growth of bubbles on hydrophobic (unwetted) surfaces.

Some of the greatest analytical and experimental contributions on pool boiling have come from pioneers like Kutateladze, Rohsenow, etc. Kutateladze [17] has proposed the following correlation which predicts pool boiling in terms of Nusselt and Prandtl numbers.

$$\frac{h_{nb}d}{k} = 0.44 \left[\left(\frac{10^{-4}qp}{gh_{fg}\rho_v} \right) \left(\frac{\rho_f}{\rho_f - \rho_v} \right) \right]^{0.7} P_r^{0.35} \tag{1}$$

Rohsenow [18] studied pool boiling analytically and proposed the following correlation to determine the heat transfer coefficient which is quite commonly used by researchers.

$$h = \frac{1}{C_{sf}} \left[\frac{C_{pf}q}{h_{fg}} \right] \left[\frac{q}{\mu_f h_{fg}} \left(\frac{\sigma}{g(\rho_f - \rho_v)} \right)^{\frac{1}{2}} \right]^{-n} \left[\frac{\mu C_p}{k} \right]_f^{-(m+1)} \tag{2}$$

In this calculation, m is taken as 0 and C_{sf} as 0.0015 which is the empirical constant of stainless steel and water surface fluid combination.

In the mid 90s Gorenflo [19] proposed a fluid specific reduced pressure correlation and included the effect of surface roughness to calculate the heat transfer coefficient, based on German VDI approach [20]. His method uses a reference heat transfer coefficient h_o, specified for each fluid at the following reference conditions of $p_{ro} = 0.1$, $R_{po} = 0.4$ μm, and $q_o = 20,000$ W/m². The nucleate boiling heat transfer coefficient at other conditions of pressure, roughness and heat flux is then calculated relative to the reference heat transfer coefficient using the following expression.

$$h_{nb} = h_o F \left(\frac{q}{q_0} \right)^{nf} \left(\frac{R_p}{R_{p0}} \right)^{0.133} \tag{3}$$

Pressure correction factor F is

$$F = 1.2p_r^{0.27} + \left(2.5 + \frac{1}{1 - p_r} \right) p_r \tag{4}$$

The effect of reduced pressure on the exponent nf for the heat flux term is given by

$$nf = 0.9 - 0.3p_r^{0.3} \tag{5}$$

The surface roughness R_p is set to 0.4 μm when unknown. The above correction factors are for all fluids except for water and helium; for water the corresponding correction factors are,

$$F = 1.73p_r^{0.27} + \left(6.1 + \frac{0.68}{1 - p_r} \right) p_r^2 \tag{6}$$

and,

$$nf = 0.9 - 0.3p_r^{0.15} \tag{7}$$

Compared with the research efforts in thermal conductivity and forced convective heat transfer, relatively few studies have been carried out on the boiling heat transfer involving phase change. Of late, studies are also carried out on surface coating using Nichrome/Platinum wire as testing surface [13, 15] and flat surface [24]. This work explores the effect of CuO nanoparticles coating formed due to boiling induced precipitation in distilled water on CHF, in addition to studies on transient characteristics in pool boiling, using a cylindrical surface.

2 Pool boiling experiment

The pool boiling experiments were carried out after preparing and characterizing the nanofluid as discussed below.

2.1 Preparation and characterization of nanofluids

The CuO nanoparticles (purity ≥ 99 %, Average particle size = 50 nm, Specific surface area = 80 m²/g) manufactured by NaBond Technologies Corporation Limited were procured to prepare CuO nanofluid. A two-step method conducted by dispersing different amount of CuO nanoparticles into water was utilized for preparing CuO nanofluids with various weight concentrations. Initially, the fluid was stirred in a high speed mixer at 18,000 rpm for 3 h and the sample was tested for agglomeration. To ensure further homogenization, nanofluid was stirred in a sonicator for 3 h. The fluid sample was collected in a glass vessel for particle size analysis. The particle size distribution was ranged from to 10 to 120 nm. Figure 1 shows the TEM image of CuO nanoparticles dispersed in distilled water taken after 60 min of sonication.

2.2 Experimental set up

The experimental apparatus is shown schematically in Fig. 2. The test chamber is a boiling vessel of 80 mm diameter and 200 mm length made up of SS 316, fitted with flanges at the top and at the bottom. The top flange of

Fig. 1 Characteristics of nano-fluid: **a** TEM image of CuO nano-particles **b** particle size distribution
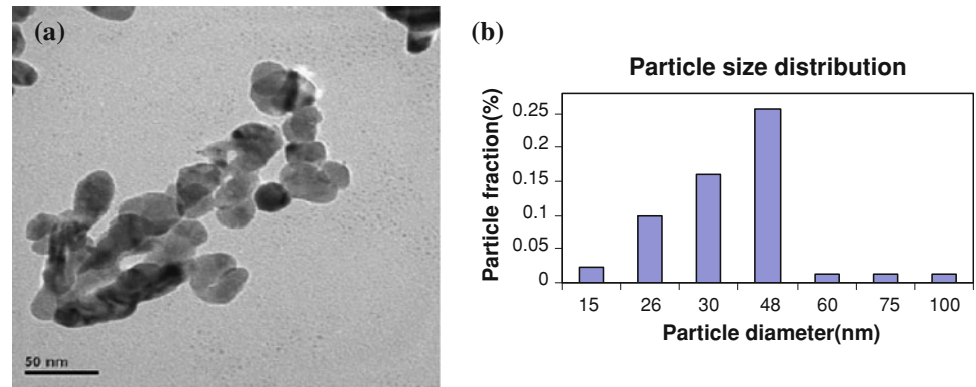

the vessel has provisions for nanofluid charging, condenser cooling water inlet and outlet lines, vacuum pump line, pressure transducer and thermocouples connections. The bottom flange has provisions for mounting the test heater section and drain pipe. The test section is heated by an electrical heating element of 1 kW capacity. The heating element is connected to a wattmeter through a dimmer stat to vary the heat input during the experimentation.

Liquid and vapor temperatures are measured by using two K type thermocouples placed inside the boiling vessel. The boiling vessel is well insulated with glass wool of 50 mm thickness, to ensure minimum heat loss to the surroundings. The radial heat loss from the cylindrical surface with and without insulation was respectively 9.3 W (1.17 %) and 54.7 W (6.84 %) at the maximum heat input of 800 W. The test section is a vertical cylindrical surface of 6 mm diameter and 17 mm length. Two thermocouples are embedded into the cylindrical surface; 5 mm apart at a depth of 1 mm from the periphery. Since the heating surface is completely immersed in the liquid, most of the heat input is utilized for convective pool boiling with negligible room for conduction loss. The conduction heat loss from the tip of the heater to the base was found to be 3.8 W, calculated at the maximum heat input of 800 W. The details of the heater along with the thermocouple locations at section A–A are shown in Fig. 3.

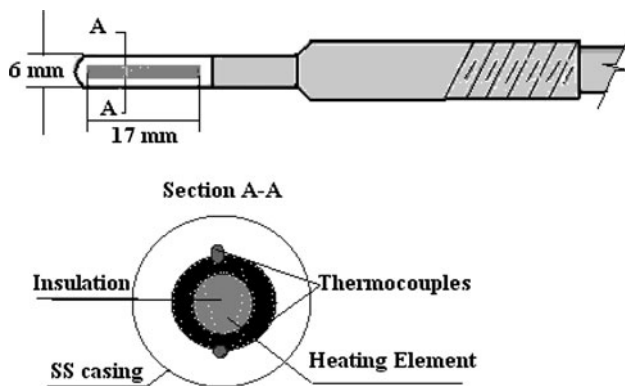**Fig. 2** Schematic diagram of experimental setup
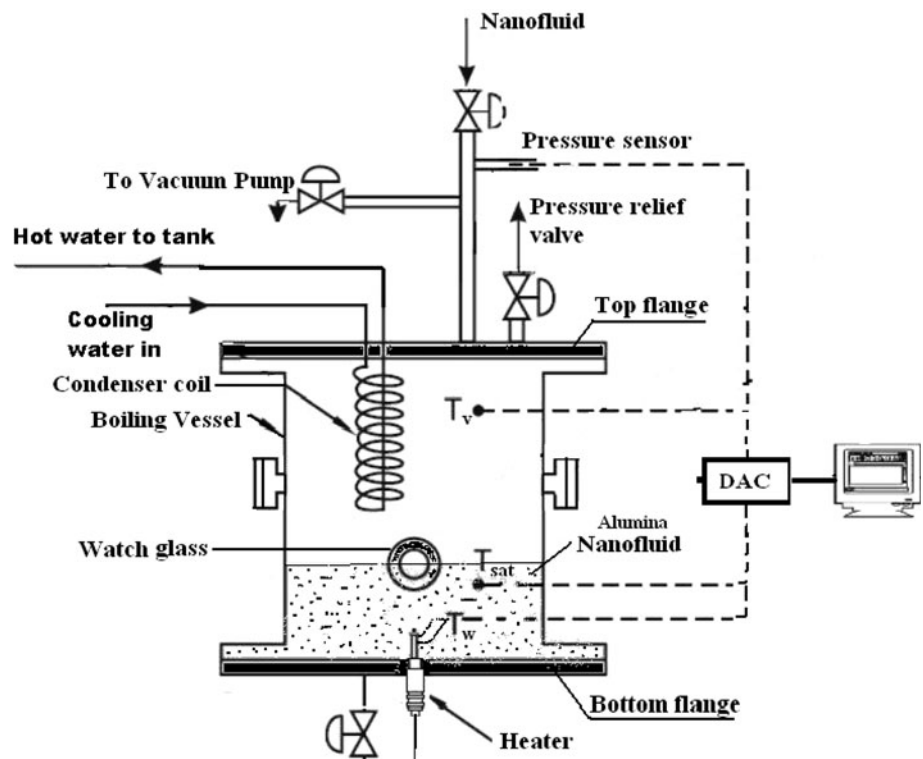
Fig. 3 Heater details with cut section of heater at A–A

2.3 Experimental procedure

Before starting the experiment, the boiling chamber was evacuated using a vacuum pump. The boiling vessel was then filled with CuO-water nanofluid. Heat input to the test section was given in steps by operating the variac. System pressure was maintained atmospheric. Pressure sensor sensed any variation in system pressure and operated the pump, by circulating cooling water through condenser coils. After ensuring the steady state conditions, liquid, vapour, heater surface temperatures and heat input were logged on to the Data Acquisition System. Care was taken not to reach burnout point (input maintained around 850 W maximum) to avoid melting of the heater itself. The heat flux q was calculated using the following relation.

$$q = \frac{Q}{A} \tag{8}$$

Heat transfer coefficient between the surface and the liquid is calculated by applying Newton's law of cooling

$$h = \frac{q}{T_w - T_s} \tag{9}$$

where T_w is the average of surface temperatures recorded by thermocouples.

2.4 Experimental uncertainty

All chrome alumel K type thermocouples used in this study have an accuracy of $\pm 0.5\ \%$ full scale. The power input to the heater is measured by an accurate digital power meter with ± 1 W uncertainty. The uncertainty in temperature measurement is $\pm 1.25\ °C$. Uncertainty in length and diameter measurement is ± 0.1 mm. The resulting uncertainty in the area of the heated surface is 1.74 %. The uncertainty for the derived quantities can be estimated as explained by Holman [21] as follows.

Percentage uncertainty in heat transfer coefficient,

$$U_h = \left[\left(\frac{U_Q}{Q}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_L}{L}\right)^2 + \left(\frac{U_{T_w}}{T_w - T_s}\right)^2 \right.$$
$$\left. + \left(\frac{U_{T_s}}{T_w - T_s}\right)^2 \right]^{1/2} \tag{10}$$

The resulting maximum uncertainty in the heat flux was 1.94 %. The maximum uncertainty in the wall superheat value was 10.71 %. The maximum uncertainty in the heat transfer coefficient was 10.86 %.

2.5 Experimental reproducibility

To investigate the reliability of our boiling test apparatus and to provide the baseline for future comparison, two trial runs were conducted using CuO nanofluid with 0.1 g/l concentration on two different days. As shown in Fig. 4, all data points are clustered closely showing good repeatability of the experimental procedures and apparatus, falling within an error margin of 10 %.

3 Results and discussions

3.1 The boiling characteristics of the water based nanofluids

Figure 5 shows the pool boiling experimental results for water based CuO nanofluid at two different weight concentrations of 0.1 and 0.5 g/l at atmospheric pressure. As reported by many previous results, there is deterioration in boiling heat transfer with increased nanoparticle concentration. Besides, the higher the concentration of nanoparticles, the greater is the degradation of heat transfer rate within nucleate boiling zone. This demonstrates that the phenomenon of formation and development of nanoparticle coatings was mainly driven by vigorous vaporization in nucleate boiling regime. From the figure it can be observed
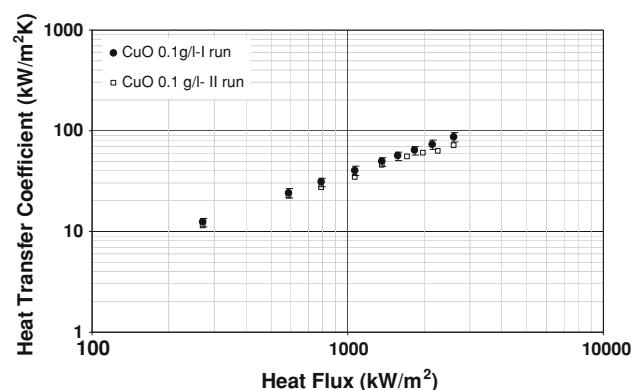

Fig. 4 Experimental reproducibility

that Rohsenow relation over predicts boiling heat transfer coefficient of water which could be attributed to the combination of surface characteristics of the heater and working conditions. However, the experimental values reasonably agree with Gorenflo relation, which takes into account the surface roughness.

3.2 Effect of nanofluid concentration

Figure 6 shows the pool boiling curve for the two concentrations of CuO nanofluid along with distilled water. Addition of CuO nanoparticles (0.1–0.5 g/l), results in shifting of boiling curve to the right indicating deterioration of boiling heat transfer. Since the range of the excess temperature in the natural convection regime of nanofluid is wider than that of pure water, the natural convection stage continues relatively longer and nucleate boiling is delayed due to higher degree of superheat of the boiling surface.

3.3 Boiling test with nanoparticle coated heater

Many studies in the past on CHF enhancement using nanofluids have attributed the reason for enhancement to better wetting characteristics of nanoparticle coating which forms during pool boiling [4], [22–24]. Kim et al. [4] in their investigation revealed that nanoparticles deposited on the heater surface during the boiling test can itself enhance CHF when tested in pure water. They used Ni–Cr wire in their studies and reported that nanoparticle coated heater surface tested in pure water can increase the CHF 1.35 times compared to the one tested in nanofluids. However, in order to have boiling induced coating of nanoparticles, it requires repeating the experiments using the same thin wire and subjecting it to multiple heating cycles and reuse the test wire in pure water. Chances are likely that any elongation or deformation of the wire surface experienced in one test may affect the subsequent tests and the experimental outcome. Best options available are, to use flat or cylindrical heater geometries. Even though Kwark et al. [24] conducted experiments using a
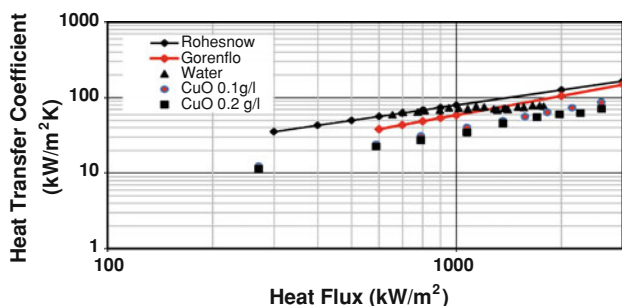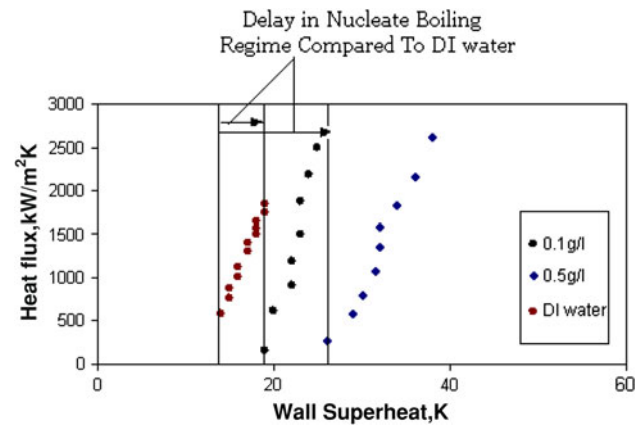
Fig. 6 Boiling curve of CuO nanofluid

10 mm × 10 mm × 3 mm flat Copper block as test surface, they didn't expose the surface to different heating cycles.

To investigate the effect of the nanocoated surfaces on pool boiling performance two different concentrations of CuO nanofluids (0.1 and 0.5 g/l) were chosen. Tests were conducted on a clean heater surface in nanofluid and nanoparticle coated heater surface in pure water. Pool boiling performance of the clean heater surface was studied by subjecting it to rigorous boiling in nanofluid. Now, this nanoparticle deposited heater surface was tested in pure water and again the pool boiling performance was studied. In the previous studies, effect of nanoparticle coating was done after removing the heater surface from the nanofluid bath and allowing it to dry. Kwark et al. [24] in their investigation have pointed out that allowing the heater surface to dry would allow the nanofluid droplets to evaporate from the hot surface and leave additional coating on the surface. This would influence the pool boiling performance. Taking note of this, tests were conducted by exposing the heater surface to 3 heating cycles of 120 min duration. After draining nanofluid and cleaning, boiling vessel was filled with pure water and pool boiling tests were conducted without allowing the heater surface to dry. The pool boiling performance of these tests is shown in Fig. 7.

From the Fig. 7, it can be observed that at lower heat fluxes the pool boiling curves for pure water and 0.1 g/l of nanofluid remain the same. But at higher heat fluxes, due to boiling induced nanoparticle coating, thermal resistance builds up deteriorating boiling heat transfer. However, the boiling curve for the 0.5 g/l of nanofluid coated heater deviates from the beginning itself due to the already existing coating.

Considering the same thickness of coating at the nanofluid concentrations (0.1 and 0.5 g/l) tested, it is expected that the critical heat flux enhancement should also be the
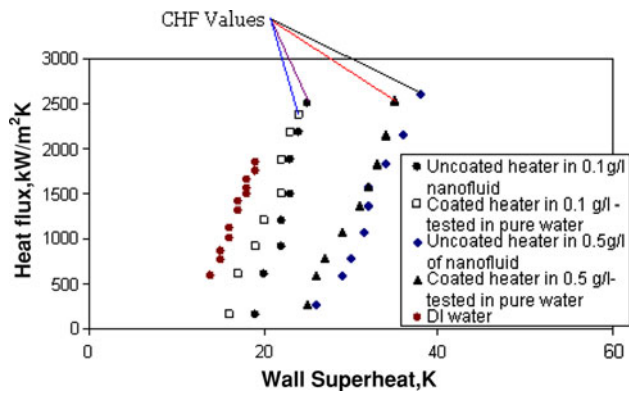
Fig. 5 Comparison of experimental data with popular correlations

Fig. 7 Pool boiling curves tested with uncoated and nanoparticle coated heater

Fig. 8 Surface roughness of clean and nanoparticle coated heater with 0.1 g/l of nanofluid **a** uncoated heater tested in nanofluid (0.1 g/l) **b** coated heater (0.1 g/l) tested in pure water

same in case of nanoparticle coated heater. With 0.1 g/l of nanofluid concentration it was observed that critical heat flux enhancement with nanoparticle coated heater was around 4.75 % lesser when compared with clean heater surface tested in nanofluid. This indicates possibility of detachment of some nanoparticle coating from the heater surface at lower concentration of 0.1 g/l, reducing the heat flux or surface temperature. At the higher concentration (0.5 g/l) of nanofluid, the reduction in heat flux was around 2.93 % when compared with clean heater surface tested in nanofluid. However, for the bare heater tested in CuO nanofluid, CHF was enhanced by 35.83 and 41.68 % respectively at 0.1 and 0.5 g/l concentration of nanofluid. For the nanoparticle coated heater surface obtained by boiling induced precipitation using 0.1 and 0.5 g/l concentration of nanofluid and tested in pure water, CHF was enhanced by 29.38 and 37.53 % respectively. In other words, at higher nanofluid concentration, CHF enhancement using nanoparticle coated heater tested in pure water was equally good compared with an uncoated heater tested in nanofluid. In order to verify the change in surface coating, surface roughness of the clean heater surface and nanoparticle coated heater surface was measured for both the concentrations tested. This is represented in Fig. 8 below. The surface roughness measurement shows that clean heater surface has Ra value of 0.33 µm before testing in 0.1 g/l of nanofluid. After the second test with nanoparticle coated heater, the surface roughness decreased to 0.25 µm indicating a smoother surface.

Figure 9a, b show the surface roughness of the heater surface measured just after concluding the boiling experiment with uncoated heater tested in 0.5 g/l of CuO nanofluid and nanoparticle coated heater tested in pure water respectively. The surface roughness measured 0.14 µm indicating sufficient coating formed over the surface and the nanoparticles accumulated in the micro cavities of the heater surface [5] thus smoothing the surface further. Same
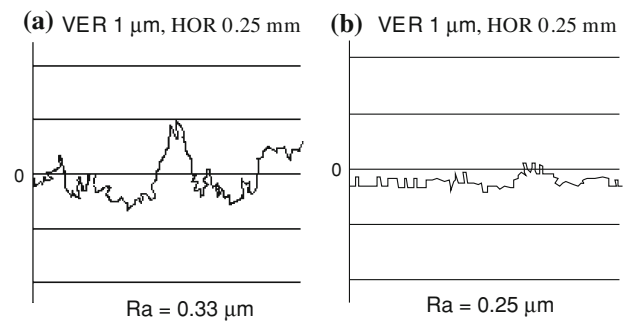
heater was now carefully mounted for the second test and pool boiling experiment was conducted in pure water. After the experiment the surface roughness of the heater was again measured which was now 0.16 µm. This indicates that some nanoparticles detached from the surface during boiling and increased the roughness of the heater surface reducing boiling heat transfer. From the experiments it can be concluded that there is a minimum nanoparticle coating required to produce maximum CHF enhancement. The experimental findings here are on the similar lines with Kwark et al. [24]. However, Kim et al. [7] reported that nanoparticle coated heater surface tested in pure water results in CHF enhancement higher than that achieved with nanofluids.

The experimental results clearly show that modification of the heater surface associated with nanoparticle deposition is responsible heat flux enhancement. The reliability of nanoparticle coating was tested by repeating the experiment with nanoparticle coated heater tested with 0.5 g/l of nanofluid. Since each run takes around 3 h, only three cycles were tested to assess the ability of the heater surface to retain the nanoparticles. The data predicted in all the three runs fall within an error margin of 6 %. The results
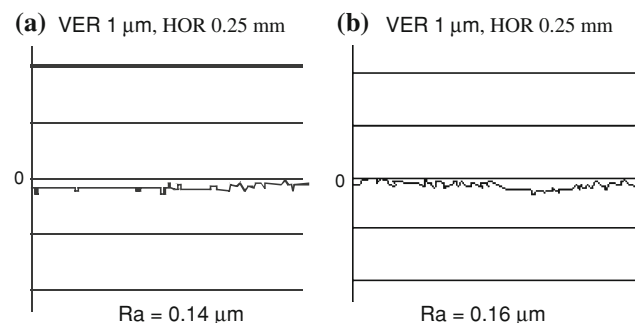

Fig. 9 Surface roughness of heater with 0.5 g/l of nanofluid **a** uncoated heater tested in nanofluid (0.5 g/l) **b** coated heater (0.5 g/l) tested in pure water
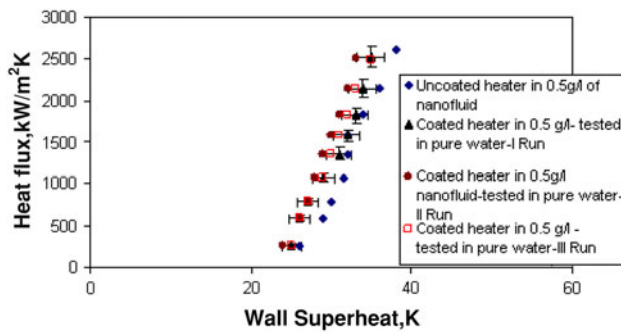
Fig. 10 Reliability test of 3 runs for nanoparticle coated surface in pure water

Fig. 11 Pool boiling curve—exhibition of transient characteristics at constant heat fluxes

shown in Fig. 10 indicate that boiling induced precipitation results in firm coating of nanoparticles over the surface.

3.4 Boiling test for transient characteristics

During pool boiling with nanofluid it is evident that the heater surface modifies continuously. Hence the boiling curve may exhibit transient characteristics. This was investigated by conducting experiments using 0.1 g/l of CuO nanofluid. To accomplish this, the heat flux was increased in constant increments, until it reached 1,000 and 1,500 kW/m^2 respectively. Without further increasing or decreasing the heat flux, boiling was continued for 90 min. After waiting for 90 min, heat flux was slowly increased till the CHF value. These results are presented in Fig. 11 along with the original pool boiling curve drawn without any waiting time period. Initial stages of pool boiling behaviour are almost same and the curves are identical. However, when time limit of 90 min was imposed with constant heat flux at 1,000 and 1,500 kW/m^2 respectively, the boiling curve discontinued and shifted towards the right. This means prolonged exposure of the heating surface to nanofluid results in degradation of boiling heat transfer. Furthermore, the higher the time of exposure with constant heat flux, the greater will be the magnitude of degradation. Higher wall superheat resulting due to this, favour the nanoparticle deposition on the heater surface. As pointed out by Stutz et al. [15], the CHF enhancement depends on the covering rate of the heated surface by nanoparticles. It reaches a maximum when the heater is entirely covered with nanoparticles and then decreases slowly when the thickness of the coating increases. The CHF increase is related to the increase in wettability induced by the nanostructured coating. Therefore, the CHF increase is more noticeable with a poorly wetted surface (water) than with a highly wetting fluid (nanofluid) [16]. For nanofluid, the observed increase in CHF is mostly due to the increase in heat transfer area when the nano porous layer is formed. The reason for critical heat flux
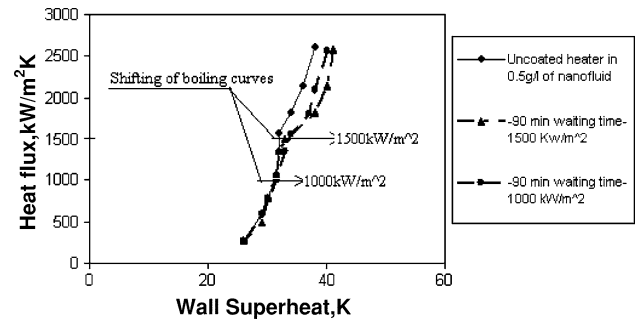
enhancement is due to other factors like surface wettability [4, 16, 23] governing it.

4 Conclusions

A series of pool boiling experiments were conducted to investigate the effect of nanoparticle coating on boiling heat transfer, with two concentrations of CuO nanofluid at different heat fluxes till the critical value. Pool boiling performance of pure water was compared with nanoparticle coated surface tested in pure water and uncoated surface tested in CuO nanofluid. Experimental outcome of the present study are listed below.

For the bare heater tested in CuO nanofluid, CHF was enhanced by 35.83 and 41.68 % respectively at 0.1 and 0.5 g/l concentration of nanofluid. Delay in transferring into the nucleate boiling regime, meant surface modification of the heater due to incessant coating until CHF. The surface roughness measurement showed heater surface modification during pool boiling process.

For the nanoparticle coated heater surface obtained by boiling induced coating using 0.1 and 0.5 g/l concentration of nanofluid and tested in pure water, CHF was enhanced by 29.38 and 37.53 % respectively. This means, nanoparticle coated heater tested in pure water clearly shows better heat flux characteristics which is nearly comparable with the performance of an uncoated heater tested in nanofluid.

Varying the concentrations of nanofluid changes the surface roughness. Prolonged exposure decreased surface roughness, which could be due to the deposition of nanoparticles into the micro cavities of the porous layer built up. These coated surfaces might have changed surface wettability, enhancing the CHF. This suggests that without changing the base fluid, heat transfer enhancement could be possible, by using a nanoparticle coated surface with some optimum thickness.

Pool boiling performance of nanofluid seems to be a strong function of time and applied heat flux. Longer the

duration of exposure of the heater surface, higher will be the degradation in heat transfer. The deterioration in nucleate boiling was due to increased particle coating which offer thermal resistance.

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