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INVESTIGATIONS ON BOILING-INDUCED NANOPARTICLE COATING, TRANSIENT CHARACTERISTICS, AND EFFECT OF PRESSURE IN POOL BOILING HEAT TRANSFER ON A CYLINDRICAL SURFACE

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Pool boiling experiments were conducted to study the heat transfer characteristics using low concentrations (0.0015 to 0.0077 vol%) of CuO nanofluids at and above atmospheric pressure in distilled water. The study included the following. (i) effect of pressure and concentration on heat transfer using CuO nanoparticles in distilled water, (ii) investigations on nanoparticle coating formed due to boiling-induced precipitation tested in CuO nanofluid and distilled water, and (iii) pool boiling behavior of CuO nanofluid subject to transient characteristics. The experimental outcome indicated that different concentrations of nanofluids display different degrees of deterioration in boiling heat transfer coefficients at and above atmospheric pressure. Boiling-induced precipitation of nanoparticles resulted in coating of nanoparticles. When tested in pure water, the nanoparticle-coated heater showed significant increase in critical heat flux compared with the critical heat flux of a bare heater tested in pure water. Study of the transient characteristics indicated degradation in boiling heat transfer due to prolonged exposure of the heater surface in nanofluid. Based on the experimental investigations, it can be concluded that nanoparticle coating can also be a potential substitute for enhancing the heat transfer if used in controlled quantities.

Keywords nanofluid, pressure, surface coating, transient, pool boiling

INTRODUCTION

Due to the ever-growing demand for new materials with advanced thermal properties, 21st-century research is mainly targeting means and methods of enhancing heat transfer. With increasing heat transfer rate of the heat exchange equipment, the conventional process fluid with low thermal conductivity can no longer meet the requirements of high-intensity heat transfer. Low thermal property of heat transfer fluid is a primary

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NOMENCLATURE

A	surface area (m^2)
Cp	specific heat (J/kg K)
g	gravitational acceleration (ms^{-2})
h	heat transfer coefficient (W/m^2K)
h_{fg}	latent heat of vaporization ($J\ kg^{-1}$)
L	length (m)
P	pressure (Pa)
q	heat flux ($W\ m^{-2}\ K^{-1}$)
T	temperature (K)
U	uncertainty
w	wall

Greek Symbols

ρ	density (kgm^{-3})
σ	surface tension (Nm^{-1})
μ	viscosity (m^2s^{-1})

Subscripts

c	critical
f	fluid, liquid
m	mass
nf	nanofluid
s	saturation
v	vapor

limitation to the development of high compactness and effectiveness of heat exchangers. An effective way of improving the thermal conductivity of fluids is to suspend small solid particles in the fluids [1]. Traditionally, solid particles of micrometer or millimeter magnitudes were mixed in the base liquid. Although the solid additives may improve the 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 that have suspended nanoscaled metallic or non metallic particles in base fluids. Some experimental investigations [2–6] have revealed that the nanofluids have remarkably higher thermal conductivities than those of conventional pure fluids and have great potential as substitute fluids for heat transfer enhancement.

To resolve the inconsistencies in thermal conductivity measurement, an international nanofluid properties benchmark exercise (INPBE) with more than 30 groups participating was done recently [7]. In the benchmark study, a large variety of nanofluids, comprising aqueous and non aqueous, metallic and metallic oxide particles, and spherical and elongated particles from low to high particle concentrations, were tested. Various experimental approaches were applied for the thermal conductivity measurements with no significant systematic differences due to the measurement methods. The thermal conductivity of the tested nanofluids increased with particle loading, particle aspect ratios, and decreasing base-fluid thermal conductivity. Nevertheless, all experimental data could be well explained by the classical effective medium theory for well-dispersed particles.

Godson et al. [8] measured the thermal conductivity and viscosity of silver-deionized water nanofluid with 0.3, 0.6, and 0.9 vol% concentrations and studied for temperatures between 50°C and 90°C. They reported thermal conductivity enhancement of a minimum and maximum enhancement of 27% at 0.3 vol% and 80% at 0.9 vol% at an average temperature of 70°C. The viscosity decreased with the increase in temperature and increased with increase in particle concentrations.

Shalkevich et al. [9] evaluated the effect of the particle size, concentration, stabilization method, and particle clustering on the thermal conductivity of gold nanofluids. They synthesized spherical gold nanoparticles of different sizes (from 2 to 45 nm) and prepared stable gold colloids in the range of volume fraction of 0.00025–1%. The highest enhancement in thermal conductivity was 1.4% for 40-nm-sized gold particles stabilized by EGMUDE (triethyleneglycolmono-11-mercaptoundecylether) and suspended in water with a particle concentration of 0.11 vol%. With most of the issues resolved in thermal characterization [7] of nanofluids, research is now focused on problems involving heat transfer with and without phase change.

Many studies have been carried out on the heat transfer coefficient of nanofluids in natural and forced flow [10–14]. Recently, Escher et al. [15] fabricated micro-channel heat sinks with three different channel widths and characterized their thermal performance as a function of volumetric flow rate for silica nanofluids at concentrations by volume of 0%, 5%, 16%, and 31%. They demonstrated that the relative thermal conductivity enhancement must be larger than the relative viscosity increase in order to gain a sizeable performance benefit. Furthermore, they showed that it would be preferable to increase the volumetric heat capacity of the fluid instead of increasing its thermal conductivity.

A detailed literature survey shows initial studies on pool boiling were mainly concerned with boiling heat transfer (BHT) coefficients and critical heat flux (CHF) values. You et al. [16] and Vassallo et al. [17] showed in their experimental findings that BHT was unaffected but that CHF increased significantly. Kim et al. [18] investigated role of nanoparticle deposition and surface wetting characteristics by measuring the static contact angle over the heater surface. Das et al. [19] studied the role of surface roughness, particle size, and nanoparticle concentration on nucleate BHT. Sefiane [20] explained the CHF enhancement due to structural disjoining pressure and contact pinning. Kim and Kim [21] reported in their experimental findings about the modification of heater surface due to nanoparticle coating, which resulted in CHF enhancement of about 160%.

Most of these studies carried out to date are limited to the thermal characterization of nanofluids without phase change (boiling, evaporation, or condensation). Nanoparticles in nanofluids can play a vital role in two-phase heat transfer systems. There is a great need to characterize nanofluids in boiling and condensation heat transfer.

Rohsenow [22] proposed the following correlation to determine the heat transfer coefficient, which is quite commonly used by researchers:

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

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.

Compared with the research efforts in thermal conductivity and forced convective heat transfer, relatively few studies have been carried out on BHT, and they are all limited in the pool boiling field with a lack of consistency in the published results. Understanding the heat transfer characteristics of nanofluids is very much in an infant stage, especially the effect of pressure, exhibition of transient behavior, and more importantly, effect of boiling-induced surface coating. This article intends to explore more on the effect of CuO nanoparticles coating formed due to boiling-induced precipitation in distilled water and transient characteristics in pool boiling apart from the study on effect of pressure.

POOL BOILING EXPERIMENT

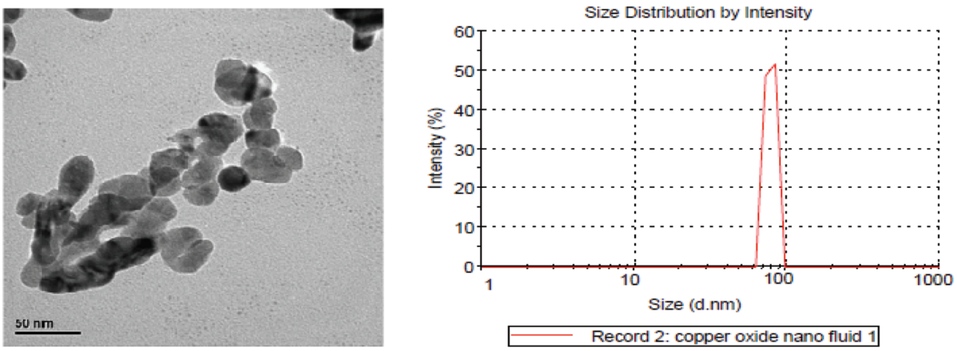
The pool boiling experiment was carried out after preparing and characterizing the nanofluid as discussed below.

Preparation and Characterization of Nanofluids

CuO nanoparticles (purity $\geq$ 99%, average particle size = 50 nm, specific surface area = 80 m^2/g) manufactured by NaBond Technologies Corporation Limited (Hong Kong) were procured to prepare the nanofluid. Preparation of the nanofluid and characterization is an important step to be followed before experimentation. The test fluid should not agglomerate during experimentation and should be homogeneous. To ensure homogenization, one can use dispersants or a sonicator. In this study, dispersants were not used for stabilization, as the addition of dispersants would influence the heat transfer characteristics of nanofluids. The nanofluid was stirred in a sonicator for 3 h. The test fluid sample was collected in a glass vessel, and the particle size was confirmed to be within the average diameter specified by the manufacturer. Figure 1 shows the transmission electron microscopy (TEM) image of nanoparticles dispersed in distilled water having spherical shapes (provided by the manufacturer) along with particle size distribution.

Pool Boiling Experiments

Figure 2 shows the schematic diagram of the experimental set-up. It consists of 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. Provisions are made on the top flange for nanofluid charging, condenser cooling water inlet and outlet lines, vacuum pump line, pressure transducer, and thermocouples connections. On the bottom flange, provisions are made for mounting the test heater section and drain. The test section is a cylindrical vertical surface of 6-mm diameter and 17-mm length with two thermocouples embedded into the surface 5 mm apart at a depth of 1 mm on the periphery. The test section is heated



(a) (b)

Figure 1. Characteristics of nanofluid: (a) TEM image of CuO nanoparticles and (b) particle size distribution. (color figure available online)

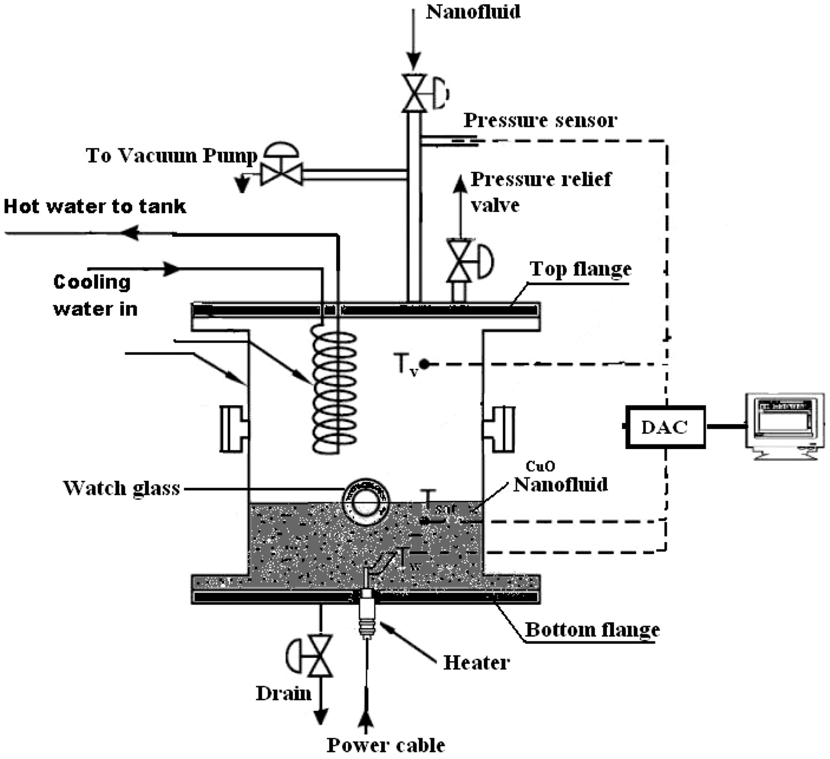


Figure 2. Schematic diagram of experimental set-up.

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 experimentation.

Two thermocouples placed inside the boiling vessel are used to measure liquid and vapor temperatures. The boiling vessel is well insulated to ensure minimum heat loss to the surroundings. Figure 3 shows details of the vertical heater surface.

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 into the surrounding atmosphere.

Before starting the experiment, the boiling chamber was evacuated using a vacuum pump. The boiling vessel was then filled with CuO–water nanofluid. The experimentation was carried out at and above atmospheric conditions. Heat input to the test section was given in steps by varying the variac until reaching CHF but below the burnout point. The set pressure was maintained constant throughout the experiment by using a condenser through which cooling water is circulated. After ensuring steady-state conditions, liquid, vapor, heater surface temperatures, and heat input were logged in the data acquisition system. Care was taken not to reach burnout point (input maintained around 800 W maximum) to avoid melting of the heater itself. The heat flux q was calculated using the following relation:

$$q = \frac{Q}{A}. \tag{2}$$

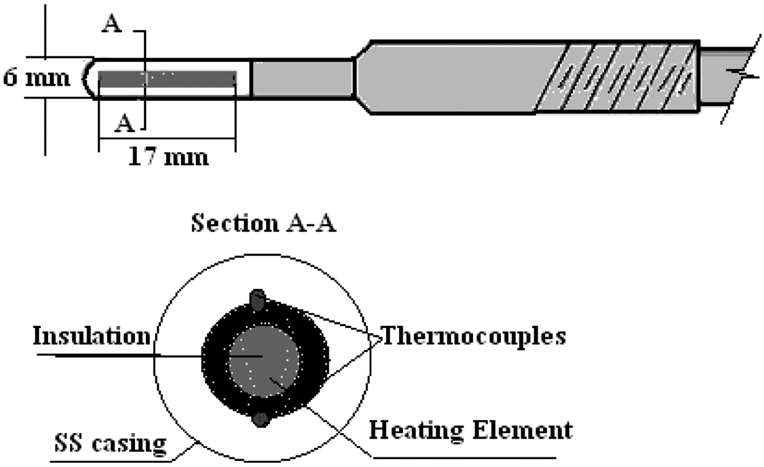


Figure 3. Details of the heater showing thermocouple locations.

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

$$h = \frac{q}{T_w - T_s}, \tag{3}$$

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

Experimental Uncertainty

All chrome alumel K-type thermocouples used in this study have an accuracy of ± 0.5% at full scale. The power input to the heater was measured by an accurate digital power meter with ± 1 W uncertainty. The uncertainty in temperature measurement is ± 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 [23] as follows.

The percentage uncertainty in heat transfer coefficient is calculated as

$$U_h = \left[\left(\frac{Uf_Q}{Q}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_L}{L}\right)^2 + \left(\frac{U_{T_w}}{T_w - T_s}\right)^2 + \left(\frac{U_{T_s}}{T_w - T_s}\right)^2\right]^{\frac{1}{2}}. \tag{4}$$

The resulting maximum uncertainty in the heat flux was 1.51%. The maximum uncertainty in the heat transfer coefficient was 1.94%.

Experimental Reproducibility

Experimental reproducibility was verified by conducting two trial runs using CuO nanofluid with 0.0015 vol% concentration on two different days. The results given in Figure 4 show that experimental outcome is reliable and falls within an error limit of 10%.

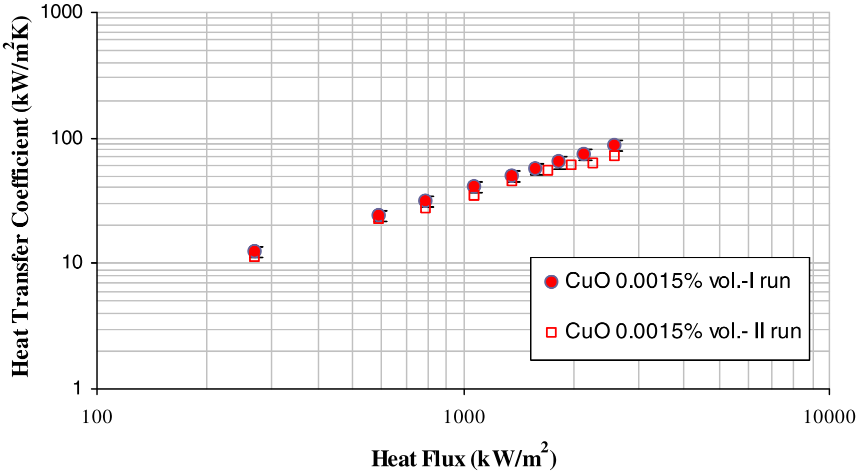


Figure 4. Experimental repeatability. (color figure available online)

RESULTS AND DISCUSSION

As mentioned above, though the main aim of present study is to investigate the pool boiling behavior of a CuO nanofluid-coated heater due to boiling-induced precipitation in pure water, some preliminary studies are also made to investigate CHF enhancement using different volume concentrations of nanofluid at and above atmospheric conditions. Based on the experimentation with CuO nanoparticles in distilled water, boiling characteristics of water based CuO nanofluid at different concentrations are discussed in what follows.

Boiling Characteristics of Water-Based Nanofluids

Figure 5 shows the pool boiling experimental results for water-based CuO nanofluid at two different volume concentrations of 0.0015% (0.1 g/l) and 0.0046% (0.3 g/l) in distilled water under atmospheric pressure. As reported by many previous results, there is deterioration in the BHT coefficient with increased nanoparticle concentration. From the figure, it can be observed that the Rohsenow relation over-predicts the BHT coefficient of water, which could be attributed to the combination of surface characteristics of the heater and working conditions.

Comparison between experimental data using nanofluids and the Rohsenow correlation show that the correlation has great potential to predict the pool boiling behavior with an appropriate modified liquid-surface combination and changed physical properties of the base fluid.

Effect of Nanofluid Concentration

Figure 6 shows the pool boiling curve for the two concentrations of CuO nanofluid along with distilled water. The addition of CuO nanoparticles (0.0015 vol% to 0.0077 vol%) results in shifting of the boiling curve to the right, indicating deterioration in BHT. In case of nanofluids, the natural convection stage continues relatively longer,

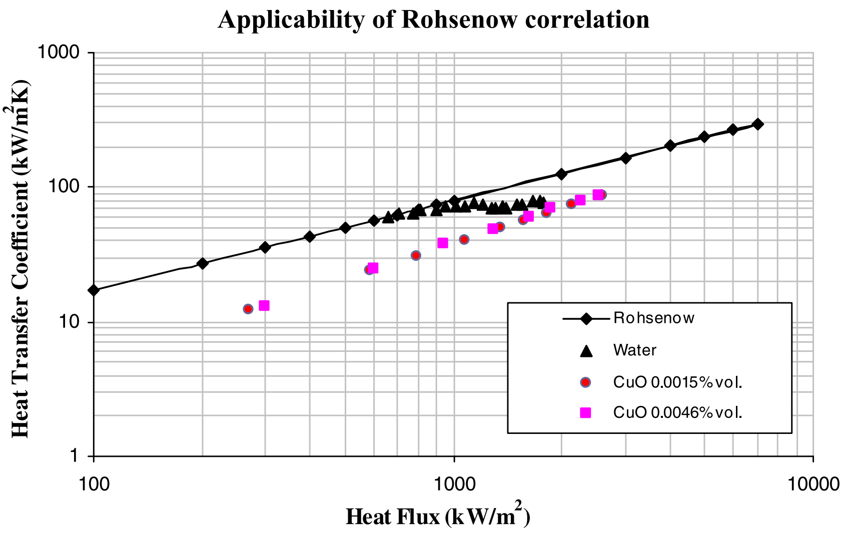


Figure 5. Comparison of experimental data with Rohsenow correlation. (color figure available online)

and nucleate boiling is delayed due to the higher degree of superheat of the boiling surface. This is because the range of the excess temperature in the natural convection regime of nanofluid is wider than that of pure water.

Effect of Pressure

Figure 7 shows the relation between heat flux and excess temperature for distilled water and 0.0015 vol% CuO nanofluid at different pressures ranging from 1 to 5 bar. The BHT is significantly affected by adding an extremely small amount of nanoparticles. The boiling curve of the working fluid at each pressure appears to be the same. As the pressure is decreased, it is clear that the curve shifts to a higher value of excess temperature.

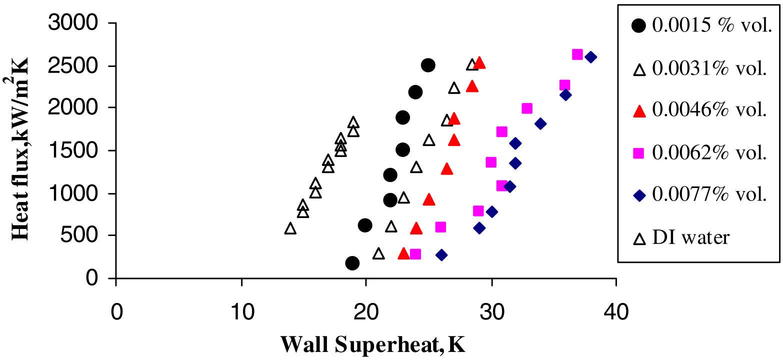


Figure 6. Pool boiling curve for CuO nanofluid at atmospheric pressure. (color figure available online)

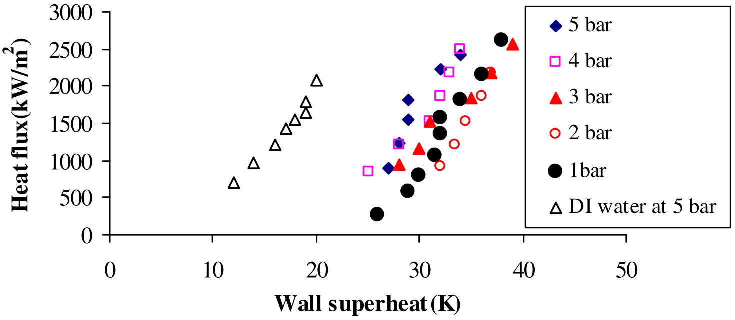


Figure 7. Pool boiling curve for CuO nanofluid (0.0015 vol%) at different pressures. (color figure available online)

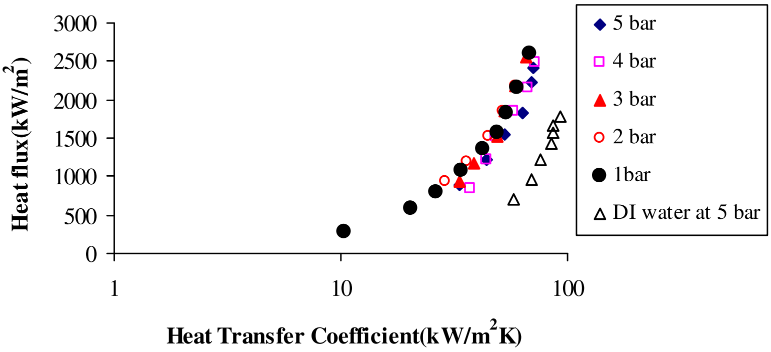


Figure 8. Heat flux versus heat transfer coefficient for CuO nanofluid (0.0015 vol%) at different pressures. (color figure available online)

Figure 8 shows the variation of the heat transfer coefficient with heat flux. It can be seen that the heat transfer coefficient increases with increase in heat flux for both water and nanofluid at higher pressures.

The effect of pressure on the heat transfer coefficient can be clearly seen at the higher value of heat flux. The heat transfer coefficient is much higher for a higher value of heat flux than for a lower value. Further, at very low heat fluxes, there is almost no effect of pressure on the heat transfer coefficient. At a given pressure, the variation may be described by the German VDI [24] relationship, $h = Cq^n$, where C is a constant that includes the effect of pressure and surface characteristics of the heater. The values of C and n were separately calculated for each concentration using the experimental data (number of data points = 152), and the average values of C and n were taken to predict the final correlation, as shown in Table 1.

Table 1. Error estimation of predictive model

CuO in deionized (DI) water (g/l)	C	n	Mean error (%)	RMS error (%)
0.1–0.5	0.047	0.8085695	11.5677	4.43

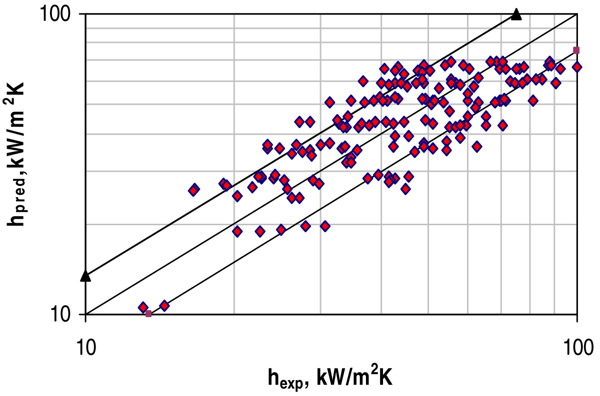


Figure 9. Predicted versus experimental values of heat transfer coefficient. (color figure available online)

Figure 9 shows predicted versus experimental values of the heat transfer coefficient based on data points for different volume concentrations of CuO nanofluid at pressures ranging from 1–5 bar. The predicted equation agrees well within a range of +20 to −20%.

As shown in Figure 10, for 0.0077% by volume concentrations at a given higher heat flux, the excess temperature of the CuO–water nanofluid is higher than that of pure water for the entire range of measured data. This shows that at the same heat flux, the nanofluid boiled at a higher surface temperature than pure water.

The heat transfer coefficient for 0.0077 vol% concentrations of the CuO–water nanofluid when compared with pure water clearly indicates deterioration. At all pressures, the heat transfer coefficients of the nanofluid are lower than those of pure water. As mentioned above, for pure water, the heat transfer coefficient increases with increasing heat flux and pressure. However for 0.0077 vol% concentration of CuO–water nanofluid, there is a decrease in the heat transfer coefficient with an increase in pressure, as seen in Figure 11. Further, when the pressure was increased from 2 to 5 bar, the heat transfer coefficient at various pressures are closer together than those of pure water.

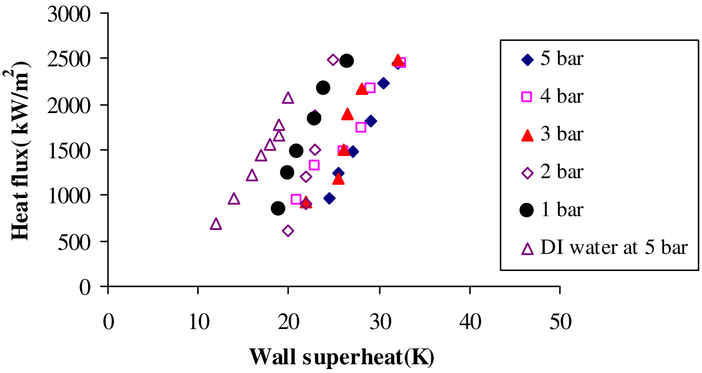


Figure 10. Pool boiling curve for CuO nanofluid (0.0077 vol%). (color figure available online)

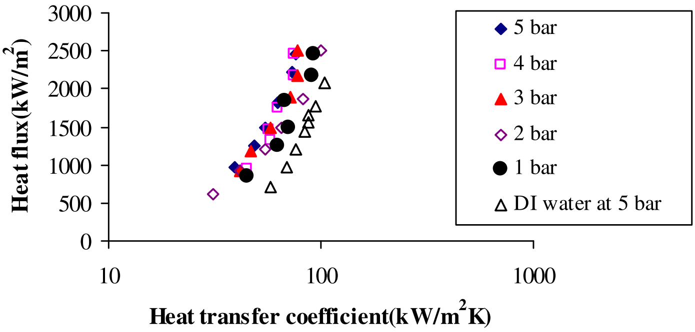


Figure 11. Heat flux versus heat transfer coefficient for CuO nanofluid (0.0077 vol%). (color figure available online)

The influence of pressure on the nucleate pool BHT, especially at high pressure, seems to be insignificant, with 0.0077 vol% concentration of CuO–water nanofluid. It is also evident from Figure 11 that the heat transfer coefficients at specific excess temperatures are almost the same at 4 and 5 bar.

Changed BHT Performance

From the above results, it is evident that inclusion of small amount of nanoparticles tends to change the pool boiling behavior, resulting in higher heat flux with a peak value only at some particle concentrations and deterioration of the heat transfer coefficient when compared with pure water. This unexpected heat transfer performance of nanofluids is opposite to their properties as a fluid. Therefore, the reasons for this conflicting performance may be related to differences in the surface characteristics between the boiling surface and nanofluids. Hegde et al. [25] found that the surface roughness of the surface considerably decreased, changing the boiling characteristics. In order to verify the modification of the heater surface due to a change in surface roughness, the surface roughness (Ra value) was measured using a surface profilometer (Mitutoyo Surftest-SJ301, Japan). The profilometer uses a diamond cone stylus of tip radius 2 μm and skid radius 40 mm with a contact force of 0.75 mN. The roughness was measured, setting a cut-off length of 2.5 mm with three sampling lengths. Four measurements were taken at diametrically opposite points of the heater along its length. After each set of measurements, the profilometer was set to auto-calibration mode, confirming to DIN roughness standard. The error due to tip convolution was taken care of by the skidless measurement using a nosepiece (part no. 12AAA210, Mitutoyo Surftest, Japan), which removes the radius with a filter (PC75, Gauss). The measurement results of the present work show that the surface roughness values of test heaters submerged in nanofluids are also decreased from 0.33 μm to 0.30 μm on average with increasing particle concentration, as shown in Figures 12 and 13, respectively.

The decrease in surface roughness could be due to the deposition of nanoparticles into the micro-cavities of the porous layer built up, as shown in Figure 13. High concentration means that the nanofluid contains more nanoparticles that move around themselves or the heated surface, which is thought to be the stochastic (Brownian) motion of the

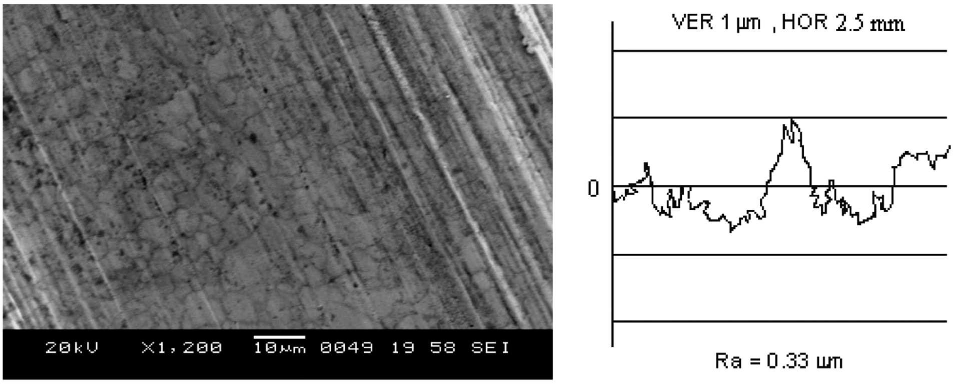


Figure 12. SEM image of bare heating surface and its surface roughness.

particles [26], and then, more agglomerates form and attach to the heated surface, which is considered to be a kind of fouling.

As far as reason increase in heat flux is concerned, it can be attributed to the nanoparticles deposition over the heater surface, resulting in higher surface temperature (the base surface temperature recorded was 153°C at 5-bar pressure and 111°C at atmospheric pressure for distilled water, while the surface temperature with nanoparticle-deposited surface was 171°C at 5-bar pressure and 147°C at atmospheric pressure) due to higher thermal conductivity of nanoparticles (thermal conductivity of CuO nanoparticles was 76.2 W/mK against the thermal conductivity of water at 0.605 W/mK). This increasing trend in heat flux would continue until a particular thickness of coating beyond which a reversal occurs. This means there is an optimum thickness of coating, which results in increased heat flux; any addition of coating beyond this will result in drop in heat flux. Further investigation in this regard is essential.

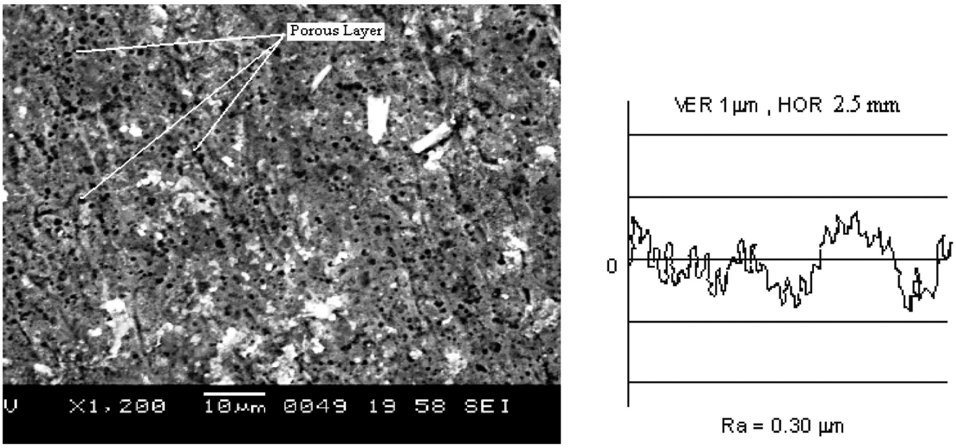


Figure 13. SEM image showing nanoparticles deposition (0.0031 vol%) on the heating surface and the corresponding surface roughness.

Boiling Test with Nanoparticle-Coated Heater

Many studies done in the past on the CHF enhancement using nanofluids have been attributed to better wetting characteristics of the nanoparticle coating that forms during pool boiling [18, 27–29]. Kim et al. [18] revealed in their investigation 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 the nanoparticle-coated heater surface can increase the CHF 1.35 times more than the one tested in nanofluids. It can be noted that to have boiling-induced coating of nanoparticles requires repeating the experiments using the same thin wire and subjecting it to multiple heating cycles and reusing it in pure water. Chances are greater that any elongation or deformation of the wire surface experienced in one test may affect the subsequent tests, thereby affecting the results. The best option available is to use flat or cylindrical heater geometries. Even though Kwark et al. [29] tested this using a 10 mm × 10 mm × 3 mm flat copper block as test surface, they did not 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 representing the lowest and the highest concentrations (i.e., 0.0015 vol% and 0.0077 vol%) were chosen, and tests were conducted on a clean heater surface in the nanofluid and nanoparticle-heated surface in pure water. The second test was based on the nanoparticle deposition on the heater surface formed out of the first test. Previous studies on the effect of nanoparticle coating were done after removing the heater surface from the nanofluid bath and allowing it to dry. Kwark et al. [29] pointed out that allowing the heater surface to dry would allow the nanofluid droplets to evaporate from the hot surface, thereby leaving an additional coating and influencing the pool boiling performance. In this work, to represent the actual heater surface conditions, tests were conducted immediately after draining the nanofluid after exposing the heater surface to three heating cycles each having a duration of 120 min without allowing the heater surface to dry. The pool boiling performance of these tests is shown in Figure 14.

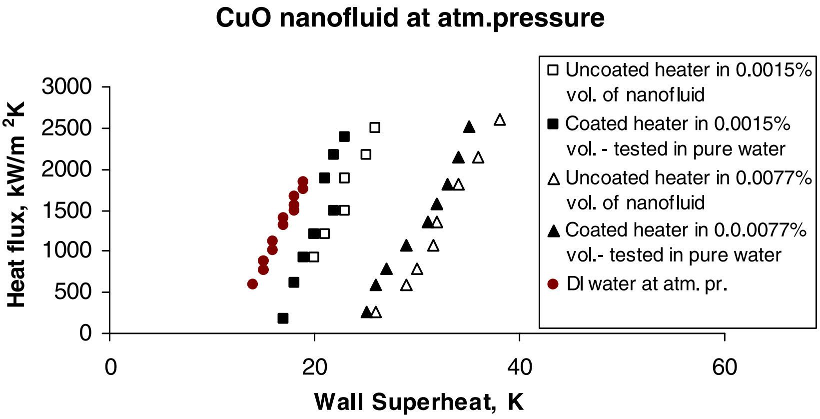


Figure 14. Pool boiling curves tested with uncoated heater in nanofluid and nanoparticle-coated heater tested in pure water. (color figure available online)

From the pool boiling curve, it can be observed that at lower heat fluxes, the pool boiling curves for pure water and 0.0015 vol% of CuO nanofluid remain the same. But at higher heat fluxes, due to boiling-induced nanoparticle coating, thermal resistance builds up, deteriorating BHT. However, the boiling curve for the nanofluid-coated heater tested in 0.0077 vol% of CuO nanofluid deviates from the beginning itself due to the already existing coating. Since the experiment was repeated without disturbing the heater surface in pure water, it is expected that the coating thickness remains same. Considering the same thickness of coating at the volume concentrations (0.0015% and 0.0077%) tested, the CHF enhancement should also be the same in the case of the nanoparticle-coated heater. However, it was observed that CHF enhancement with the nanoparticle-coated heater was around 4.75% less at 0.0015 vol% of nanofluid concentration when compared with the clean heater surface tested in nanofluid. This indicates a possibility of detachment of some nanoparticle coating from the heater surface at a lower concentration of 0.0015 vol%, reducing the surface temperature. At the higher concentration of 0.0077 vol% of nanofluid, the reduction in CHF was around 2.93% when compared with the clean heater surface tested in the nanofluid. In other words, at a higher concentration, pool boiling behavior was more or less the same. This implies that with higher concentrations, the coating is thicker, and even if some coating is removed from the surface, it has less effect on CHF. 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 concentrations tested. The surface roughness measurement showed that new heater surface has Ra value of 0.33 μm before testing in 0.0015 vol% of nanofluid. After the second test with the nanoparticle-coated heater, the surface roughness decreased to 0.26 μm, indicating a smoother surface. It can be noted that in this test, the surface was not exposed to air so that it became dry.

Figures 15a and 15b show the surface roughness of the heater surface measured just after concluding the boiling experiment with 0.0077 vol% of CuO nanofluid and the nanoparticle-coated heater tested in pure water, respectively. Since it takes some time to detach the heater from the flange, measure its surface roughness, and reattach the heater, the heater surface can be assumed to be dry before starting the second test in pure water.

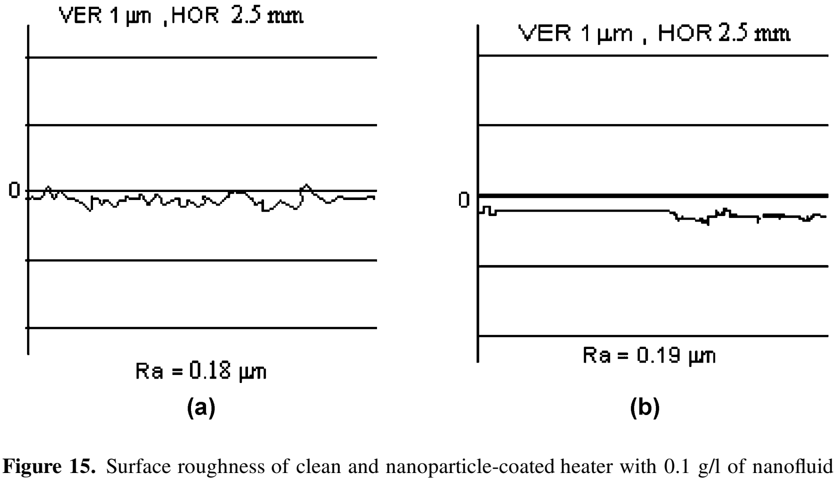


Figure 15. Surface roughness of clean and nanoparticle-coated heater with 0.1 g/l of nanofluid.

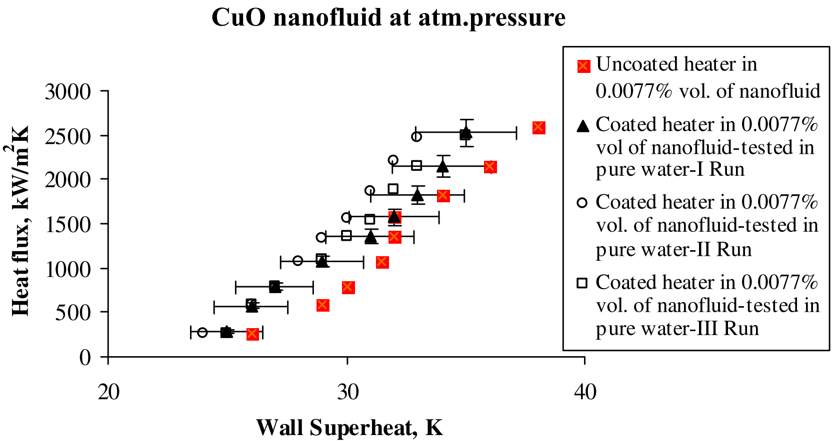


Figure 16. Reliability test of three runs for nanoparticle-coated surface in pure water. (color figure available online)

The surface roughness measured 0.18 μm, indicating that a sufficient coating formed over the surface and the nanoparticles accumulated in the micro-cavities of the heater surface [11], thus smoothing the surface further. The same heater was now carefully mounted for the second test, and a pool boiling experiment was conducted in pure water. After the experiment, the surface roughness of the heater was again measured, which was now 0.186 μm. This indicates that nanoparticle coating was almost firm during boiling, and a slight increase in the roughness of the heater surface reduced BHT. It can be concluded from the experiments that there is a minimum nanoparticle coating required to produce maximum CHF enhancement. The experimental findings here are similar to those of Kwark et al. [29]. However, Kim and Kim [21] reported that the 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 the nanoparticle coating was tested by repeating the experiment with the nanoparticle-coated heater tested with 0.0077 vol% of nanofluid. Three trial runs were taken for three consecutive days for a prolonged duration of 24 h to assess the ability of the heater surface to retain the nanoparticles. The data predicted in all three runs fall within an error margin of 7%. The results shown in Figure 16 indicate that boiling-induced precipitation results in a firm coating of nanoparticles over the surface.

Boiling Test for Transient Characteristics

During pool boiling with a 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 0.0015 vol% CuO nanofluid. To accomplish this, the heat flux was increased at constant increments, keeping the heat flux constant at 1,000 kW/m^2 and 1,500 kW/m^2, respectively, for 90 min. After 90 min, the tests were conducted in usual manner until reaching CHF value. These results are presented

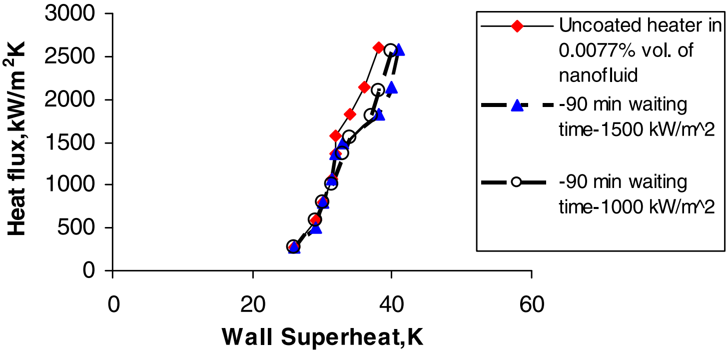


Figure 17. Pool boiling curve; transient behavior of CuO nanofluid at atmospheric pressure. (color figure available online)

in Figure 17 along with the original pool boiling curve drawn without any waiting time period. Initially pool boiling behavior is almost the same, and the curves are identical. However, when the time limit of 90 min was imposed with constant heat flux condition of 1,000 kW/m^2 and 1,500 kW/m^2, respectively, the boiling curve discontinues and shifts toward the right. This means that prolonged exposure of the heating surface to a nanofluid results in degradation of BHT. Furthermore, the higher the time of exposure with constant heat flux, the greater the magnitude of degradation will be. The resulting higher wall superheat favors the nanoparticle deposition on the heater surface. The reason for constant heat flux enhancement is due to other factors, such as surface wettability [28], governing it.

CONCLUSIONS

Experimental investigations of pool BHT of CuO nanofluids on a vertical heating surface with volume concentrations ranging from 0.0015% to 0.0077% in distilled water was done at and above atmospheric pressure. Investigations were primarily aimed at finding the effect of nanoparticle coating formed on the heater surface due to boiling-induced precipitation. The investigation led to the following conclusions.

- CHF was enhanced significantly, even at very low concentration of nanoparticles. The main reason was the increase in surface temperature of the heater in the presence of nanoparticles due to the nanoparticle coating.
- The surface roughness measurement and the corresponding SEM images of the heater surface taken for different concentrations of nanofluids before and after pool boiling tests confirmed that CHF enhancement of nanofluids was closely related to the surface microstructure and enhanced topography resulting from the deposition of nanoparticles.
- The study also revealed that modification of the heater surface results from a change in concentration, leading to decreased surface roughness. The decrease in surface roughness could be due to the deposition of nanoparticles into the microcavities of the porous layer built up due to the stochastic (Brownian) motion of the particles.

- Addition of CuO nanoparticles results in shifting the boiling curve to the right, indicating deterioration in BHT. In the case of nanofluids, the natural convection stage continues relatively longer, and nucleate boiling is delayed or a higher degree of superheat of the boiling surface is needed for boiling. The deterioration in nucleate boiling was due to increased particle coating beyond an optimum thickness, thereby inhibiting heat transfer from the test surface.
- The CHF value reached a maximum and then remained almost constant in magnitude, suggesting that thickness of deposition matters in deciding the critical value, which, in turn, can affect BHT.
- The effect of pressure seems to have played no role in the pool boiling behavior, as heat transfer coefficient at a specific excess temperature remained the same at higher pressures.
- Boiling-induced precipitation of a nanoparticle continuously modifies the heater surface. The surface roughness measurement showed heater surface modification during pool boiling process. The nanoparticle-coated heater tested in pure water clearly shows a better CHF characteristic, which is nearly comparable with the performance of an uncoated heater tested in a nanofluid. This suggests that a nanoparticle-coated surface with some optimum thickness could be a better future option for enhancing heat transfer.
- Pool boiling performance of a nanofluid seems to be a strong function of time and applied heat flux. The longer the duration of exposure of the heater surface, the higher the degradation in heat transfer will be. The deterioration in nucleate boiling was due to increased particle coating; this shows transient behavior of the nanofluid in pool boiling.

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