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Experimental study on CuO nanoparticles in distilled water and its effect on heat transfer on a vertical surface[†]

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Abstract

The pool boiling characteristics of dilute dispersions of CuO nanoparticles in water were studied at atmospheric pressure on a vertical heating surface. Experimental investigation of different weight concentrations of nanoparticles revealed significant enhancement in heat flux and deterioration in pool boiling. Out of many reasons, nanoparticles coating the heater surface was believed to be the reason behind this. Subsequent inspection of the heater surface showed nanoparticles coating the surface, forming a porous layer. To substantiate the nanoparticle deposition and its effect on heat flux, an investigation was performed by measuring the surface roughness of the heater surface before and after the experiment. While SEM images of the heater surface revealed nanoparticle deposition, measurement of surface roughness of the heater surface confirmed it. Formation of the porous layer on the heater surface as revealed by SEM images provided an excellent location for nucleation sites enhancing heat transfer. However, deterioration in nucleate boiling at different weight concentrations indicated some phenomenon is working behind this.

Keywords: CuO nanofluid; Pool boiling; Surface roughness; Vertical surface

1. Introduction

The thermal conductivity measurement of nanofluids was the main focus in the early stages of nanofluid research. Recently, studies have been carried out on the heat transfer coefficient of nanofluids in natural and forced flow. Most 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.

When a liquid is in contact with a surface maintained at a temperature above the saturation temperature of the liquid, boiling will eventually occur at that liquid-solid interface. The unique features of boiling and condensation are that heat transfer to and from the liquid can occur without influencing the fluid temperature, the rates of heat transfer and the heat transfer coefficient are much higher than those of the normal convection process due to the latent heat associated with phase change, and a high rate of heat transfer is achieved with small temperature difference.

Pool boiling CHF is the point where nucleate boiling goes through a flow regime transition to film boiling with a continuous vapor film separating the heater and the liquid. CHF is the condition where the vapor generated by nucleate boiling becomes so large that it prevents the liquid from reaching and rewetting the surface.

Apart from some of the earlier studies on phase-changing heat transfer using nanofluids [1-4], some of the recent research findings in pool boiling heat transfer are briefed here as follows.

Kwark et al. [5] experimentally studied the pool boiling behavior of low concentration nanofluids (≤ 1g/l) over a flat heater at 1 atm. They guessed that boiling nanoparticles produces a thin film on the heater surface and is responsible for an increase in CHF. Their study also indicated nanoparticle deposition resulted in transient characteristics in the nucleate boiling heat transfer. Further investigation revealed that micro layer evaporation during nanofluid boiling was responsible for the formation of a nanoparticle coating on the heater surfaces.

Janusz T. Cieslinski et al. [6] have recently conducted pool boiling experiments to establish the influence of nanofluids' concentration as well as tube surface material on heat transfer characteristics at atmospheric pressure. They used a horizontal

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test surface made of smooth copper and stainless steel tubes having 10 mm OD and 0.6 mm wall thickness. They selected two nanofluids containing Al_2O_3 and Cu nanoparticles with concentrations of 0.01%, 0.1%, and 1% by weight. Their results indicated that independent of concentration, nanoparticle material (Al_2O_3 and Cu) has almost no influence on the heat transfer coefficient during pool boiling of water-Al_2O_3 or water-Cu combination nanofluids on a smooth copper tube. While the heater material did not affect the boiling heat transfer in 0.1 wt.% of the water-Cu nanofluid, a distinctly higher heat transfer coefficient was recorded for a stainless steel tube than for a copper tube for the same heat flux density, independent of concentration.

Coursey and Kim J. [7], in their experimental findings using ethanol-based Al_2O_3 nanoparticle, found that even if the concentration was increased by over two orders of magnitude, no enhancement or degradation of heat transfer was observed during boiling on a glass or gold surface. It was attributed to the highly wetting nature of ethanol. For ethanol- Al_2O_3 nanofluids and copper surfaces, nucleate boiling was improved with increasing nanoparticle concentration.

Liu and Liao [8] examined nanofluids, i.e., mixtures of a base fluid (water and alcohol), nanoparticles (CuO and SiO_2) and surfactant (SDBS), and nanoparticle-suspensions consisting of the base liquid and nanoparticles during pool boiling on the face of a copper bar having 20 mm diameter. The boiling characteristics of the nanofluids and nanoparticle-suspensions were poorer compared to that of the base fluids.

Narayan et al. [9] studied the influence of tube orientation on the pool boiling heat transfer of water-Al_2O_3 nanofluids with concentrations of 0.25%, 1%, and 2% by weight on a smooth tube of diameter 33 mm inclined at 0°, 45°, and 90°. They found that the horizontal orientation gave maximum heat transfer and boiling performance deteriorated with increase in nanoparticle concentration.

Trisaksri and Wongwises [10] tested R141b-TiO_2 nanofluids while boiling on a horizontal copper cylinder of 28.5 mm diameter. They discovered that adding a small amount of nanoparticles did not affect the boiling heat transfer, but addition of TiO_2 nanoparticles at 0.03% and 0.05% by volume resulted in deterioration in boiling heat transfer. Moreover, the boiling heat transfer coefficient decreased with increasing particle volume concentrations, especially at higher heat flux.

Kathiravan et al. [11] investigated the boiling of water-Cu and water-Cu-SDS nanofluids on a 300 mm square stainless steel plate. They revealed that copper nanoparticles caused a decrease in the boiling heat transfer coefficient with water used as the base liquid. The heat transfer coefficient decreased with increase in concentration of 0.25%, 0.5%, and 1% by weight of nanoparticles for both water-Cu and water-Cu-SDS nanofluids.

The above literature survey shows critical heat flux (CHF) can be increased by addition of solid nanoparticles to common base fluids such as water, ethylene glycol, etc. In spite of research in the field of nanofluids as briefed above, understanding the heat transfer characteristics of nanofluids is very much at an infant stage. Thus, this paper intends to explore the effect of CuO nanofluid in pool boiling and its subsequent role in heat transfer enhancement.

Table 1. Properties of CuO nanofluid.

Items	CuO
Content of CuO	≥ 99%
Average particle size	50 nm
Specific surface area	80 m^2/g

2. Pool boiling experiment

2.1 Preparation and characterization of nanofluids

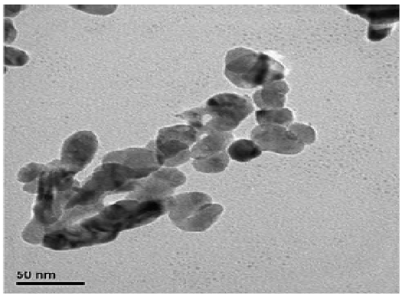
CuO nanoparticles manufactured by NaBond Technologies Corporation Limited were procured to prepare the nanofluid by a two-step method; dispersing dry nanoparticles into the base liquid (distilled water) followed by sonication. The analysis was performed according to the NaBond company standard, and the CuO has the properties given in Table 1 below.

Since the characteristics of nanofluids are not only governed by the kind and size of the nanoparticles but also their dispersion status in the base fluid, it is essential to have a test fluid sample without any agglomeration. To ensure no agglomeration, any one of the following methods suggested by Xuan and Li [12] viz. changing the pH value of the suspension using dispersants or using ultrasonic vibration can be followed. All these methods are aimed at changing the surface properties of suspended particles and subsequently suppressing the formation of particle clusters. 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 high speed homogenizer for 9 hours and kept for 60 minutes in idle condition. Later, the test fluid sample was collected in a glass vessel and particle size analysis was done. Test results from the particle size analyzer confirmed nanoparticle size in the range of 10 nm to 100 nm with an average of 50 nm, as provided by the manufacturer. Fig. 1 shows the TEM image of nanoparticles dispersed in distilled water with spherical particles.

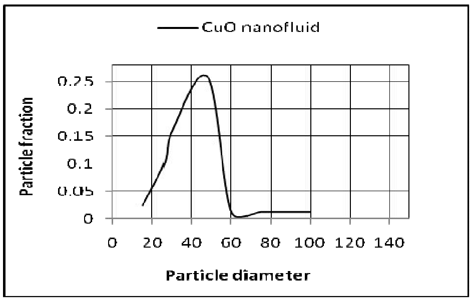
Fig. 2 shows the photograph of the test samples at different weight concentrations taken after 60 minutes with negligible agglomeration.

2.2 Pool boiling experiments

Fig. 3 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 SS 316 flanges at the top and at the bottom. The top flange has provisions for liquid charging, condenser cooling water inlet and outlet, vacuum pump, pressure transducer and thermocouples to measure



(a) TEM photograph of CuO nano-particles



(b) Size distribution of the nano-particles

Fig. 1. Characteristics of nano-fluid.

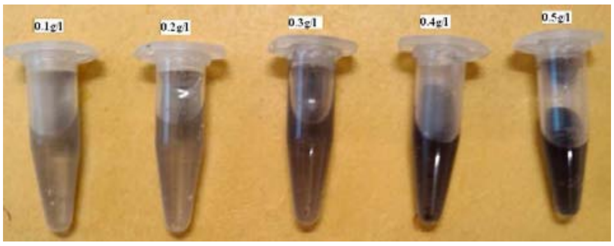


Fig. 2. Test samples at different weight concentrations.

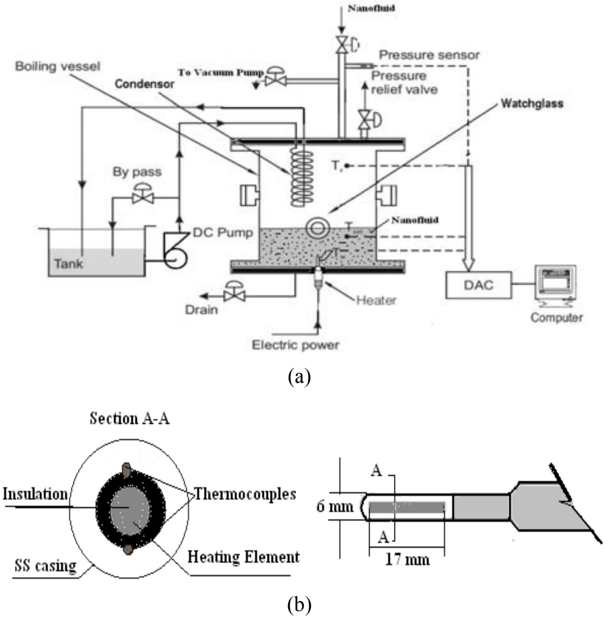


Fig. 3. (a) Schematic diagram of experimental setup; (b) Test section of the heater.

liquid and vapor temperatures. The bottom flange has provisions 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 on to the surface 5 mm apart at a depth of 1 mm on the periphery. An average of the surface temperatures recorded by these thermocouples is taken as wall temperature to compute the heat transfer coefficient. 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 experimentation.

Two thermocouples are set inside the boiling vessel: one each to measure liquid and vapor temperatures. The boiling vessel is well insulated to ensure minimum heat loss to the surroundings. 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. It can be noted that to avoid conduction heat loss, the following care was taken while fabricating the system:

The cylindrical heating surface was completely immersed in the liquid so that maximum heat is utilized for pool boiling with negligible conduction axial heat loss.

The body of the heater beyond the heating length of 17 mm was made of stainless steel, which has low thermal conductivity. The protruding length (threaded portion) of the heater beyond the bottom flange exposed to the atmosphere was kept to a minimum of 12 mm in length.

To verify the axial conduction loss beyond the heating length, the surface temperature was recorded using a high sensitivity temperature probe, with less than 2% conduction loss.

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 atmospheric conditions. Heat input to the test section was given in steps by the variac. The set pressure was maintained constant throughout the experiment by using a condenser through which cooling water was circulated. A pressure transducer and a proportional integral derivative (PID) pressure controller were used to sense and maintain the required pressure. The PID senses the pressure level in the boiling chamber through pressure transducer and compares it with the set value fed to it. After ensuring steady state conditions, liquid, vapor, and heater surface temperatures; system pressure; and heat input were logged in the Data Acquisition System. Care was taken not to reach the critical value of heat flux (input maintained around 800 W maximum) as this would lead to a ‘burn out’ point, melting the heater itself. The heat flux q was calculated using the following relation:

$$q = \frac{Q}{A}. \qquad (1)$$

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

$$h = \frac{q}{T_w - T_s} \tag{2}$$

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

2.3 Experimental uncertainty

Major sources of uncertainty include the measurements of test surface temperature, liquid temperature, system pressure and heat input. The experimental uncertainty, including parameters like applied heat input in W, liquid temperature (T_L), and measurement in concentration (w) were calculated using the following relation proposed by Holman [13]:

$$U_{qHF} = q_{HF}\left\{\left(\frac{U_{W\max}}{W_{\max}}\right)^2 + \left(\frac{U_{P\max}}{P_{\max}}\right)^2 + \left(\frac{U_{T_W}}{T_w}\right)^2 + \left(\frac{U_{T_L}}{T_L}\right)^2 + \left(\frac{U_w}{w}\right)^2\right\}^{\frac{1}{2}}. \tag{3}$$

The uncertainties of the applied wattage, pressure (in this paper only atmospheric pressure is considered), surface and liquid temperatures and concentrations were respectively found to be 1%, 0.7% and 1%. From the above analysis, the maximum uncertainty for pool boiling heat flux was estimated to be 4.96%.The maximum uncertainty in the wall superheat values was ± 1°C. The maximum uncertainty in the heat transfer coefficient was 10.86%.

3. Results and discussion

Pool boiling behaviour of CuO nanofluid at different weight concentrations was studied at atmospheric pressure. The experimental outcome indicated deterioration in boiling heat transfer with CuO nanofluid when compared to distilled water. The characterization of the heater surface was done qualitatively and quantitatively by taking the SEM image and measuring the surface roughness, respectively, which are discussed in detail below.

3.1 The boiling characteristics of the water-based CuO nanofluid

Fig. 4 shows the pool boiling experimental results for water-based CuO nanofluid at different weight concentrations ranging from 0.1g/l to 0.5g/l of distilled water at atmospheric pressure. To compare the pool boiling performance of water and nanofluids, the saturation temperature of pure water was taken as 100°C for water and nanofluid.

3.1.1 Experimental reliability

In order to check the reliability of the apparatus, the experimental results were compared with the data predicted by the well-known Rohsenow correlation. Rohsenow [14] proposed the following correlation to determine the heat transfer coefficient, which is quite commonly used by researchers.

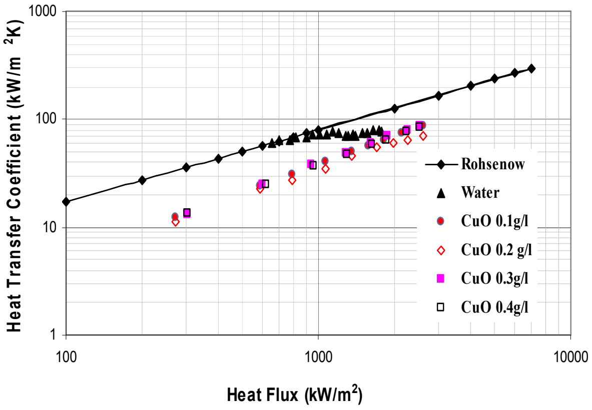


Fig. 4. Applicability of Rohsenow correlation.

$$h = \frac{1}{C_{sf}}\left[\frac{C_{pf}q}{h_{fg}}\right]\left[\frac{q}{\mu_f h_{fg}}\left(\frac{\sigma}{g(\rho_f - \rho_v)}\right)^{\frac{1}{2}}\right]^{-n}\left[\frac{\mu C_p}{k}\right]_f^{-(m+1)} \tag{4}$$

In this equation, m is taken as 0 and C_{sf} as 0.0043 which is the empirical constant of stainless steel and water surface-fluid combination.

From Fig. 4 it can be observed that boiling heat transfer coefficient of water agrees reasonably well with the Eq. (4), having a deviation of 6.5% even at higher values of heat flux. Comparison between experimental data using nanofluids and the Rohsenow correlation shows that the correlation has great potential to predict pool boiling behavior with an appropriate modified liquid-surface combination and changed physical properties of the base fluid.

3.1.2 Predictive model

We know that the boiling heat transfer coefficient is a function of boiling heat flux, and the parameters influencing heat transfer are (i) heat flux, (ii) liquid properties, (iii) pressure, and (iv) surface characteristics of heater. The German Heat Atlas (VDI Warm atlas) suggests correlations as ratio of heat transfer coefficients taking the above factors into consideration. To predict the heat transfer coefficient, the correlation used is $h = Cq^n$, where C is a constant that includes the effects of pressure and surface characteristics of the heater.

The predictive model was developed by calculating the value of C and n for each concentration of nanofluid using the experimental data (no of data points = 46), and the average value of C and n was taken to predict the final correlation, as shown in Table 2.

The prediction accuracy of the correlation was assessed and the prediction errors were evaluated using the following definitions:

Table 2. Error estimation of predictive model.

CuO in DI water(g/l)	1/C	1/n	Mean error (%)	RMS error (%)
0.100	16.43	1.19	0.19	0.19
0.200	13.73	1.21	-0.03	0.04
0.300	16.44	1.12	-0.09	0.09
0.400	13.09	1.16	-0.16	0.17
0.500	14.61	1.11	0.13	0.15
Average	14.86	1.16		

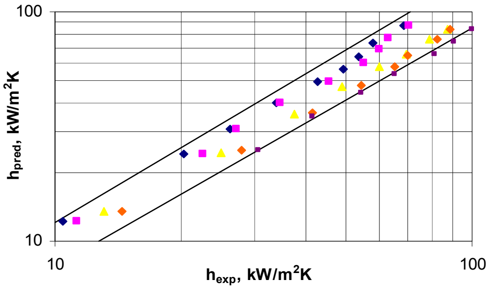


Fig. 5. Experimental and predicted values of heat transfer coefficient.

$$Error = \left(\frac{h_{pred} - h_{\exp}}{h_{\exp}}\right) \tag{5}$$

mean error is given by

$$\text{Mean error} = \sum_{i}^{n} \frac{Error_i}{n} \tag{6}$$

and, finally, RMS error is given by

$$\text{RMS error} = \sqrt{\sum_{i}^{n} \frac{Error_i^2}{n}}\ . \tag{7}$$

The following graph shows the plot of experimental and predicted values of heat transfer coefficient based on data points for different weight concentrations of CuO nanofluid at atmospheric pressure. The predicted equation agrees well within the range of +20 to -20.

3.2 Effect of nanofluid concentration

Experiments were carried out to elucidate the pool boiling of CuO-water nanofluid in distilled water at 0.1g/l to 0.5g/l of distilled water, and the nucleate pool boiling heat transfer of pure water and nanofluid at different weight concentrations were compared. As shown in Fig. 6, different concentrations of nanofluids display different degrees of deterioration in boiling heat transfer. At 0.1g/l concentration, boiling heat transfer increases to 33% when compared with pure water. This indicates that even by adding a small amount of nanoparticles, the boiling heat transfer is affected to a greater extent. Further addition of CuO nanoparticles (0.2g/l to 0.5g/l), shifts the boiling curve to the right, indicating deterioration of boiling heat transfer. Fig. 6 shows clear distinctions between the natural convection stage and nucleate boiling stage. In nano-fluids, the natural convection stage lasts relatively longer and nucleate boiling is delayed, indicating that the boiling surface must be superheated to a higher degree for boiling. This is because the range of the excess temperature in the natural convection regime of the nanofluid is wider than that of pure water.

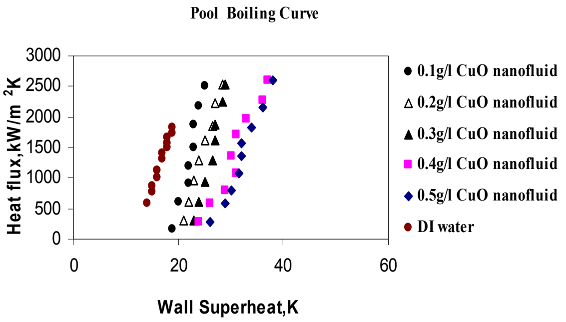


Fig. 6. Boiling curve for five different weight concentrations of CuO nanofluid.

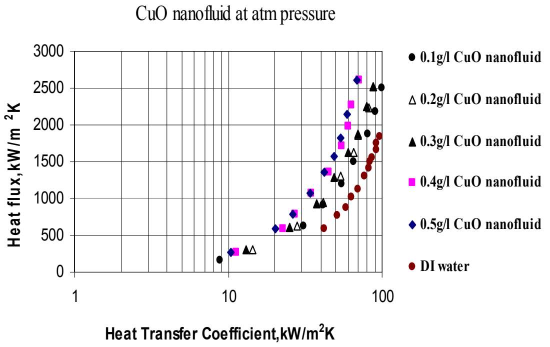


Fig. 7. Heat flux v/s Het transfer coefficient.

As shown in Fig. 7, at the same heat flux, the heat transfer coefficient at higher-concentration nanofluids is lower than that at lower concentrations across the range of heat flux. At higher heat flux, the effect of concentration is prominent. Further, it can be observed that for a particular concentration of nanofluid (0.4g/l in this case) the heat flux is the highest for the concentration range tested and stays more or less the same with increased concentration. Out of many reasons, one possible explanation may be the deposition of nanoparticles over the heating surface, the effect of which is discussed in the next section.

3.3 Discussion on changed boiling performance

From the above results, it is evident that inclusion of a small amount of nanoparticles tends to change the pool boiling behavior, resulting in higher heat flux at different particle concentrations, but deteriorates the boiling heat transfer coefficient when compared with pure water. This unexpected heat transfer performance of nanofluids opposes their properties as

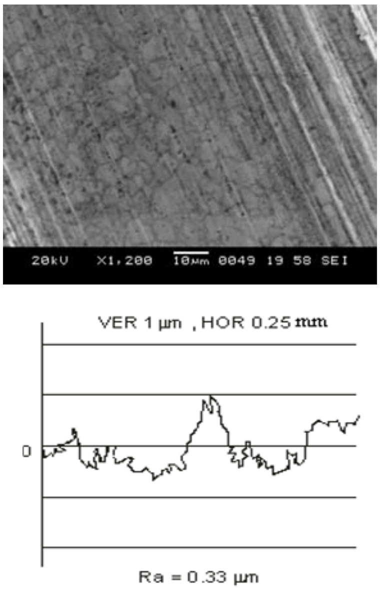


Fig. 8. SEM image of bare heating surface and its surface roughness.

a fluid. Therefore, the reasons for this conflicting performance may be related to differences in the surface characteristics between the boiling surface and nano-fluids. Hegde et al. [15] found that the roughness of the heater surface considerably decreased changes in the boiling characteristics. In order to confirm the nanoparticle coating over the heater surface, SEM images of the bare surface of the heater were taken before starting the experiment and the surface roughness (Ra value) was measured using the Mitutoyo Surf test.

The SEM image of the bare heater surface shown in Fig. 8 had a surface roughness of 33 µm.

The SEM images were taken again for 0.2g/l and 0.5g/l concentrations of nanofluid and the surface roughness was measured after each run using the same heater. At 0.2g/l concentration of nanofluid, the surface roughness decreased to 30 µm from the initial value of 33 µm, indicating nanoparticle coating. The SEM image showed micro cavities over the nanoparticle-coated surface as shown in Fig. 9.

This value is slightly higher than the surface roughness of the heater surface at 0.4g/l of water, which measured 0.22 µm. Since the surface roughness remained more or less the same, the heat flux also remained at 2612 kW/m^2 and 2604 kW/m^2 respectively at 0.4g/l and 0.5g/l of nanofluids, as shown in Fig. 6 above. As high concentrations of the nanofluid contain more nanoparticles that move around themselves on the heated surface (which is thought of as the stochastic (Brownian) motion of the particles [16]) they form more agglomerates and attach to the heated surface, which is considered as a form of fouling. Since fouled surfaces are known to decrease the contact angle with pure water and nanofluid droplets, the wettability is enhanced by the porous layer on the surface [17].

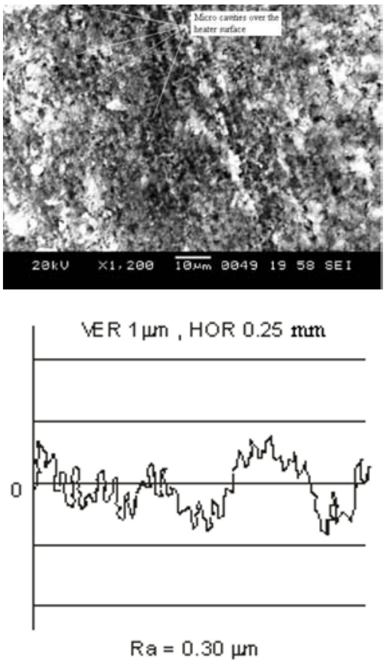


Fig. 9. SEM image showing nanoparticle deposition (0.2g/l) on the heating surface and surface roughness.

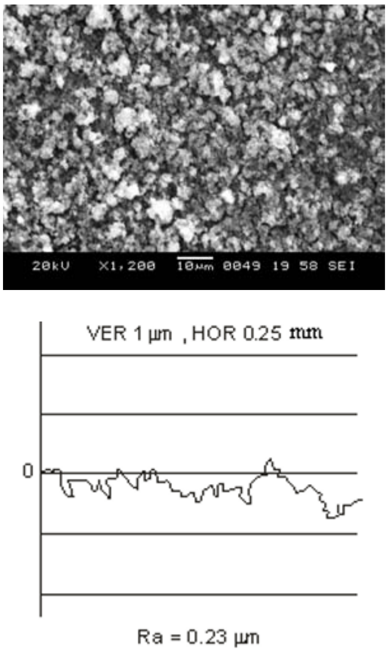


Fig. 10. SEM image showing nanoparticle deposition (0.5g/l) on the heating surface and surface roughness.

The reason for the increase in heat flux when compared to pure water can be attributed to the nanoparticle deposition over the heater surface resulting in higher surface temperature due to the higher thermal conductivity of nanoparticles.This increasing trend in heat flux continues until a particular thickness of coating beyond which a reversal occurs. This means there is an optimum coating thickness which results in increased heat flux. Any addition of coating beyond this will result in a drop in heat flux. Further investigation of the effects of coating thickness on heat flux is essential.

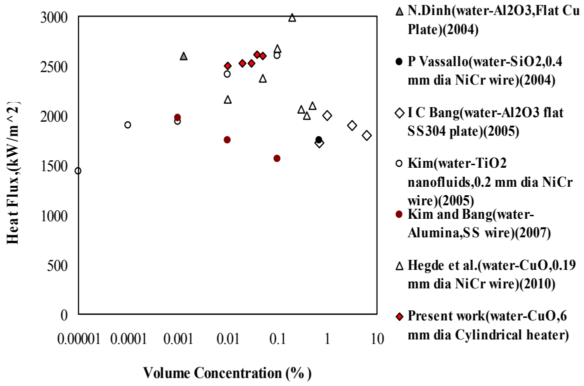


Fig. 11. Comparison of present work with earlier research contributions.

The decrease in surface roughness could be due to the deposition of nanoparticles into the micro cavities of the porous layer that builds up due to boiling-induced precipitation. With further increase in concentration to 0.5g/l, surface roughness reduced to 0.23 μm, as shown in Fig. 10.

In terms of CHF enhancement by the usage of nanofluids instead of pure water as a cooling liquid, the results of the present study are consistent with those of other works performed under atmospheric pressure, as shown in Fig. 11. The variation in the heat flux values were similar to the trend observed by Bang et al. [4], Hegde et al. [15] and Kim [18]. Wherein heat flux increased with concentration, a reverse trend was observed in the studies of Kim and Bang [17]. The reason for the quantitative differences could be attributed to the differences existing in the type or geometry of the heating surface, combinations of water-nanoparticle and their effective thermal conductivities, testing conditions, etc.

4. Conclusions

Pool boiling characteristics in CuO nanofluids were investigated on a vertical heating surface with five weight concentrations ranging from 0.1 g/l – 0.5 g/l of distilled water. The effect of CuO nanoparticles in pool boiling for each concentration was studied experimentally. Based on experimental outcome and subsequent investigations the following conclusions can be drawn:

During the experimentation, the pool boiling of CuO nanofluids with a vertical heating surface enhanced the heat flux at around 33.4% even at very low concentrations of nanoparticles (0.1 g/l) when compared to pure water.

The surface roughness measurement of the heater surface indicated decrease in surface roughness from 0.33μm to 0.23 μm. SEM images of the heater surface showed porous layer build up due to boiling-induced precipitation of nanofluid. Decrease in surface roughness can be attributed to nanoparticles filling the micro cavities formed over the surface.

Addition of CuO nanoparticles shifts the boiling curve to the right, indicating deterioration in boiling heat transfer. The deterioration in nucleate boiling could be due to increased particle coating beyond an optimum thickness, which in turn would inhibit heat transfer from the test surface.

Nomenclature

A : Surface area (m^2)
Cp : Specific heat (J/kg K)
C_{sf} : Constant for surface-fluid combination
g : Gravitational acceleration (ms^{-2})
h : Heat transfer coefficient (W/m^2K)
h_{fg} : Latent heat of vaporization (J kg^{-1})
k : Thermal conductivity ($Wm^{-1}K^{-1}$)
m : Mass concentration (g/l)
n : Number of samples
P : Pressure (N/m^2)
Q : Heat input (W)
q : Heat flux (W m^{-2} K^{-1})
T : Temperature (K)
U : Uncertainty

Greek symbols

ρ : Density (kgm^{-3})
σ : Surface tension (Nm^{-1})
μ : Viscosity (m^2s^{-1})

Subscripts

c : Critical
HF : Heat Flux
exp : Experimental
f : Fluid
max : Maximum
pred : Predicted
s : Saturation
v : Vapour
w : Wall

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