INFLUENCE OF SURFACE ROUGHNESS AND WETTABILITY OF NOVEL SURFACE ON NUCLEATE BOILING PERFORMANCE IN DEIONISED WATER AT ATMOSPHERIC PRESSURE

by

Nithyanandam THANGAVELU[a*], Senthil Kumar DURAISAMY[b], Sridharan MOHAN[c], and Dinesh SUNDARESAN[d]

[a] M.Kumarasamy College of Engineering, Karur, India
[b] Sona College of Technology, Salem, India
[c] K.Ramakrishnan College of Engineering, Tiruchirappalli, India
[d] K.Ramakrishnan College of Technology, Tiruchirappalli, India

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Pool boiling is one of the very suitable techniques for an efficient thermal management system dealing with two-phases. The present work deals with the experimental exploration of critical heat flux for safety concern and heat transfer coefficient related to the performance point of view in nucleate boiling regime of pool boiling system. The copper substrate was coated with porous copper nanoparticles by sputtering technique to the thicknesses of 250 nm, 500 nm, and 750 nm. The surface characteristics of the copper nanocoated surfaces have been analysed as a result of wettability, surface roughness, and micro-structure. The contact angle goniometer, stylus profilometer, XRD, and SEM have been employed to analyze the surface structure. The maximum augmentation of critical heat flux was 59% for the thickness of 750 nm as compared to plain copper substrate. A 99% increase in the heat transfer coefficient was achieved for 750 nm thickness surface in comparison with the plain copper surface. The tremendous augmentation in critical heat flux and heat transfer coefficient was achieved due to wetting and rewetting properties of the deionized water on the copper nanocoated surfaces. The capillary action on the copper nanostructure improves the fluid supply to the test surface and removes the heat at low wall superheat than the plain copper surface. The average roughness of the copper nanocoated surface augments the heat transfer area which tends to enhance the performance factor significantly.

Key words: *pool boiling, wettability, surface roughness, critical heat flux, heat transfer coefficient*

Introduction

The removal of heat in electronics equipments and nuclear reactor is a challenging task due to its size and higher heat generation rate. A new technology is essential to remove large amount heat from the electronics equipment and nuclear reactor. The passive cooling is of a worthy interest to transport large quantity of heat and to improve the equipment safety.

The heat transfer coefficient (HTC), reaches a maximum of 2.3 folds higher for reduced graphene oxide nanofluid at higher concentration has been reported [1]. The critical heat flux (CHF) of Al_2O_3-water based nanofluid was evidenced 7% higher than the machined

* Corresponding author, e-mail: nithynano@gmail.com

copper surface and significant enhancement of HTC was also observed [2]. The augmentation of CHF in nanofluid is not affected by the concentration of nanoparticles but in the case of HTC enhancement [3, 4]. The rewetting of active sites on the test surfaces with segmented fins has improved the HTC by two folds than the bare surface [5]. The specific geometric arrangement made on the boiling surface facilitated the excess supply of water and the effective area on the heater surface promotes the HTC enhancement [6, 7]. The HTC enhancement has been reported as a result of improved roughness and enhanced hydrophillicity. The significant enhancement of HTC was reported due to the active participation of nucleation sites [8]. The capillary effect, augmented nucleation sites and improved bubble dynamics have been recognised to promote the augmentation of the CHF and HTC [9-14]. The peak heat flux and HTC increased on the metal oxide nanostructure surfaces at high wettability due to the formation of nucleation sites and cavities [15-17]. The improved surface wettability and capillary effect enhanced the CHF and HTC of nucleate boiling for the test surface developed with nanowires of various diameters [18]. The hysteresis of contact angle, evaporation from microlayer and surface roughness has been recognised to promote the CHF augmentation [19]. A rough surface coated with reduced graphene oxide increased the rate of heat transfer by facilitating small scale bubble formation due to excellent mixing of liquid [20]. The CHF enhancement has been identified due to enhanced wickability on the hexagonal boron nitride nanostructured surfaces [21]. The fin action and improved wettability of the carbon nanotube coated surfaces increased the maximum heat flux [22]. A maximum of 41.68% CHF enhancement on nucleate boiling of copper oxide nanofluid at 0.5 g/l concentration of the nanofluid was evidenced [23]. More grooves on the heater surface offered more resistance to the bubble lifting. The aspect ratio was not the cause for the HTC enhancement in the boiling investigation of grooved surfaces [24]. Employing nanofluids have significant enhancement of CHF, but the HTC has negative impact [25]. Halloysite nanotube and water based nanofluid was employed in pool boiling applications and HTC was evidenced 5.8% larger than the base fluid [26]. The HTC of boiling nanofluid in single phase at low heat flux was found better than the two-phase [27]. An HTC enhancement ratio of 1.7 was obtained for cerium oxide nanofluid for the volume concentration of 0.007% [28]. An enhancement ratio of 1.37 was reported in the investigation of aluminum oxide and cerium oxide hybrid nanofluid in pool boiling for the volume concentration of 0.05% at low heat flux [29]. Tungsten oxide based nanofluid employed in boiling applications results in an enhancement ratio of 6.7% higher at 0.01% volume concentration [30].

From the literature, it can be clearly seen that a lot of work have been performed on the nanofluids and various patterned surfaces. At the outset, the sedimentation of nanoparticles was observed during boiling experiments in nanofluids. The deposition of nanoparticles on the test surface plays a key role for the CHF and HTC augmentation. However, the formation of a nanostructure on the surface attracts the researchers to do further investigation on the heat transfer performance.

In this study, an attempt is made to create novel pyramid like copper nanostructure on the heater surface to improve its wettability and surface roughness. The selection of coating technique is also a key factor for the high stability of thin film on the test surface. The controlled process parameters of direct current sputtering process create a pyramid like copper novel nanostructure on the boiling surface. The new structure of copper thin film on the surface creates numerous cavities, sharp peaks and valleys. These kinds of structures can facilitate the water to wet on the surface continuously. The space for wetting and rewetting due to the shape of copper structure is more beneficial for pool boiling performance improvement and CHF enhancement. Also, stability of the nanostructure has to be ensured for durability. The present study explores the effect of wetting behaviour and nanoscale roughness to enhance the HTC and CHF of nucleate boiling on copper nanocoated surfaces.

Methodology

Development of nanostructure

A plain copper surface of 1.1 cm diameter and 8 mm thickness is used to create novel copper nanostructure. The copper thin film coating was done by physical vapour deposition method. The PLASSYS MP 300 DC sputtering machine is employed to create the copper nanostructure on the copper test surface. The coating thickness has been controlled by the duration of coating. The thickness monitoring indicator is used to control the thickness of the thin film coating. The diffusion pump and rotary pumps were employed to regulate the vacuum inside the coating chamber. The working temperature was maintained at 200 °C and argon gas-flow rate was maintained at 20 cm^3/min. The vacuum inside the chamber was maintained at $6 \cdot 10^{-6}$ mbar and the working pressure was 14.6 mbar. The coating time of 20 minutes was consumed to obtain the thickness of 250 nm, 32 minutes for 500 nm, and 48 minutes was required to coat 750 nm thickness.

Experimental arrangement of pool boiling

The test specimen was placed on the heater block as shown in fig. 1 using thermal paste which tends to minimize the heat loss from the interface. Thick glass wool of insulation was used to cover the heater block to reduce the heat dissipation along radial direction. The cartridge heaters of 250 W were employed to transfer the heat to the test specimen. All four heaters were inserted tightly into the holes machined in the heater block to eliminate the contact resistance and to assure maximum heat dissipation.

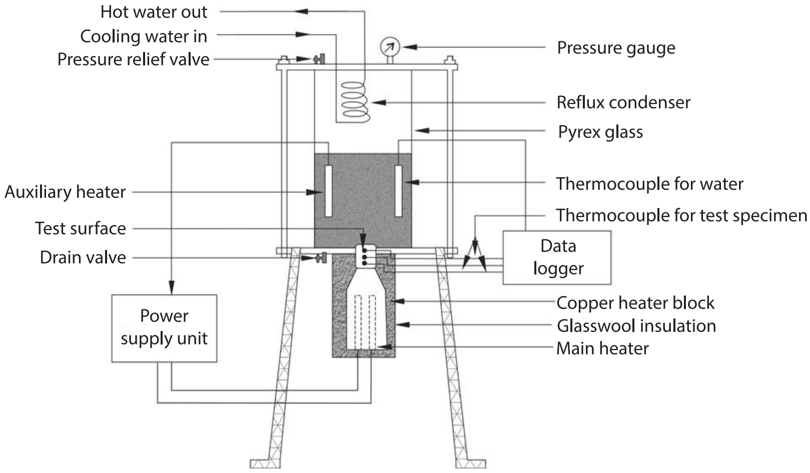

Figure 1. Experimental set-up of pool boiling in schematic illustration

An auxiliary heater was immersed in the water bath to raise the temperature to the saturation state. A constant water level was maintained in the pool boiling chamber during the entire boiling process by mounting a reflux condenser. To supply uninterrupted power for cartridge heaters, an autotransformer was utilised. The thermocouples of *K*-type were used for measuring the temperatures at some specific points of the test specimen in axial direction. The temperatures at three points in the spatial direction at uniform intervals were used to determine the temperature of test surface. The liquid saturation temperature was measured by a thermocouple immersed in the water bath. A data logger was employed to record the temperatures of water and test specimen.

Data reduction

The Taylor series approximation was applied for the calculation of spatial temperature gradient:

$$\frac{\mathrm{d}T}{\mathrm{d}x}=\frac{3T_1-4T_2+T_3}{2\Delta x} \tag{1}$$

The heat flux, q, and surface temperature, T_w, were determined from Fourier's law of heat conduction for the spatial temperature gradients upto CHF:

$$q=-k\frac{\mathrm{d}T}{\mathrm{d}x} \tag{2}$$

$$T_\mathrm{w}=T_1-q\left(\frac{X_1}{k_\mathrm{cu}}\right) \tag{3}$$

The HTC, h, was calculated by Newton's law of cooling:

$$h=\frac{q}{\left(T_\mathrm{w}-T_\mathrm{sat}\right)} \tag{4}$$

Analysis of uncertainty

Calibrated digital thermometers were used for the calibration of thermocouples using constant temperature oil bath. The uncertainty value of temperature was identified as ±0.5 °C. The uncertainty of ±0.2 mm was identified for the distance between adjacent thermocouples in axial direction of copper block. The copper thermal conductivity of 390 W/mK was taken for all the calculations of pool boiling. Kline and McClintok [31] method was followed to obtain the experimental uncertainties of the heat flux and HTC. Uncertainty of ±6.93-8.87% was estimated for heat flux data in eq. (5) and the range ±7.78-9.24% was evaluated for HTC values using eq. (6). The uncertainty of wall superheat in eq. (7) was estimated in the range of ±7.68-9.16%:

$$\frac{\omega_q}{q}=\left[\left(\frac{\omega_k}{k}\right)^2+\left(\frac{\omega_{T_1}}{T_2-T_1}\right)^2+\left(\frac{\omega_{T_2}}{T_2-T_1}\right)^2+\left(\frac{\omega_x}{x}\right)^2\right]^{0.5} \tag{5}$$

$$\frac{\omega_h}{h}=\left[\left(\frac{\omega_q}{q}\right)^2+\left(\frac{\omega_{T_w}}{T_\mathrm{w}-T_\mathrm{sat}}\right)^2+\left(\frac{\omega_{T_\mathrm{sat}}}{T_\mathrm{w}-T_\mathrm{sat}}\right)^2\right]^{0.5} \tag{6}$$

$$\frac{\omega_{T_\mathrm{ws}}}{T_\mathrm{ws}}=\left[\left(\frac{\omega_k}{k}\right)^2+\left(\frac{\omega_{T_1}}{T_1}\right)^2+\left(\frac{\omega_{T_\mathrm{sat}}}{T_\mathrm{sat}}\right)^2+\left(\frac{\omega_{X1}}{X1}\right)^2+\left(\frac{\omega_q}{q}\right)^2\right]^{0.5} \tag{7}$$

Results and discussion

Critical heat flux of plain copper surface

In the present study, the CHF of plain copper surface was found using five trials to validate the further experimental results. Initially, the test was conducted for the untreated plain copper surface. From five consecutive trials of experiments, the CHF of plain copper surface was estimated at 123.8 W/cm^2 for further validation and comparison. The results shown in tab. 1 has good agreement with the previously reported data of CHF values for the plain copper surface established from experimental and theoretical studies with an allowable percentage of errors.

Table 1. Validation of CHF for present study

Model	CHF [Wcm^{-2}]	Contact angle
[32]	152.1	–
[33]	110.8	–
[34]	135.2	–
[35]	125.9	–
[36]	102.4	–
[37]	129.2	–
[38]	109.5	CA = 83°
[39]	108.9	CA = 83°
[40]	188.6	CA = 83°
[41]	139.0	–
[42]	148.4	–
Present study	123.8	CA = 83°

It is clearly seen that in fig. 2, the experimental and few theoretical are very close to the present study. The maximum percentage error of 34% was witnessed and minimum percentage error was evidenced as 1.67%. The result of CHF for the bare copper surface indicated that the experimental study was more reliable and accurate.

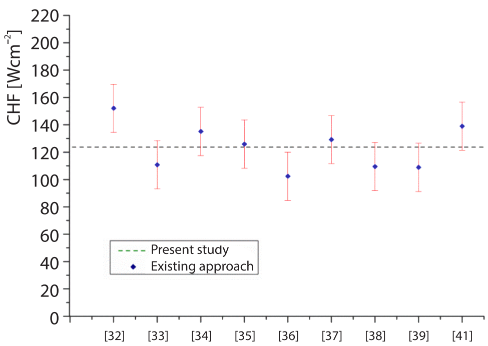

Figure 2. Comparison CHF of present study with existing approaches

Surface wettability effects

The wetting characteristics of test surface play a crucial role in pool boiling investigation. The KRUSS GmbH-FM40Mk2 water contact angle goniometer was utilised to measure the angle of contact of test fluid made on the boiling surfaces. The wettability of the copper test surface was depicted by the water contact angle. The contact angle of 250 nm thickness copper nanocoated surface was significantly low in comparison with plain copper surface and it was measured 58°. The contact angle of surface of thickness 500 nm was depicted 50° and 38° contact angle was obtained for the surface of thickness 750 nm, respectively.

The profound reduction in contact angle as shown in fig. 3 of the copper nanocoated surfaces exhibited enhanced wettability and maintained excellent hydrophillic characteristics for all the thicknesses in this study. The CHF of the surface at higher wettability was found significantly higher than the plain copper surface. It is clearly evidenced that the wettability of the surface improves the active nucleation sites and these sites serves for the bubble formation that maximises the heat dissipation in the nucleate boiling region.

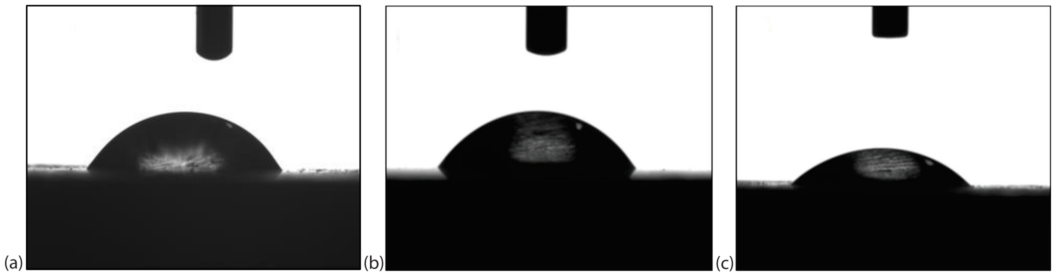

Figure 3. Wettability of copper nanocoated surfaces of thicknesses; (a) 250 nm, (b) 500 nm, and (c) 750 nm

The present investigation of pool boiling on the copper nanocoated surfaces reported that the CHF and HTC enhanced significantly in comparison with the plain copper surface. The interfacial surface tension was found very low when the wettability increases. It was observed that the bubbles generated in the nucleation sites detached easily and provides support for the formation of new bubbles. The rapid formation of the bubble and detachment of bubble from the nucleation sites formed on the test surface removes heat in a short span of time. The quick removal of heat results in the occurrence of earlier CHF. The remarkable enhancements of HTC and CHF of copper nanocoated surfaces were reported in comparison with the plain surface.

Influence of surface roughness

The surface roughness of the copper nanocoated surfaces was computed by stylus profilometer (DEKTAK XT, USA). The average surface roughness of 0.025 μm was observed for the thickness of 250 nm. A roughness of 0.092 μm was evidenced for the thickness of 500 nm and 0.143 μm for 750 nm, respectively. The experimental investigation clearly shows that the enhancement in HTC occurred for the increasing nanoscale surface roughness of the copper nanocoating. The effective area of the heat transfer is modified by the roughness of the nanocoated surfaces. The surface roughness of 0.020 μm was evidenced for the plain copper surface after the surface preparation. We all know that the HTC is in direct proportion the area of exhibited surface for heat transfer. More roughness in nanoscale of thin-film coated surface provides larger area to heat dissipation. In nucleate boiling region, the significant improvement in area enhances the HTC at lower wall superheat. But in all the cases of copper thin-film coated surface, the enhancement was found good at lower wall superheat region. But at the higher wall superheat regime, the augmentation of HTC was not significant. It is believed that the cause for significant reduction in enhancement of HTC is only due to the resistance offered by the vapour blankets formed on the heat transfer surfaces.

The reduction of enhancement was evidenced close to the occurrence of CHF. The similar trend was revealed at all thicknesses of the copper nanocoated substrates. Nevertheless, it is clearly observed that the HTC was comparatively higher value of 89.4 kW/m^{2}K at 750 nm thickness as compared to the thicknesses of 250 nm and 500 nm. Also, the HTC was achieved significantly high in all thicknesses of copper nanocoated surfaces than the plain copper substrate.

Structural effects on boiling performance

A sigma HV Carl Zeiss with Bruker Quantax field emission scanning electron microscope was utilised to record the micro-structures of the thin film coated surfaces. A surface morphological characteristic as shown in the fig. 4 has been modified as the thickness of the coating increases. The SEM images of copper thin-film surfaces revealed that the deposition was almost uniform. The crests and troughs created on the surface results with improved roughness in nanoscale. These crests, troughs and voids on the surface because of the nanocoating creates a plenty of nucleation spots involving active participation in pool boiling process.

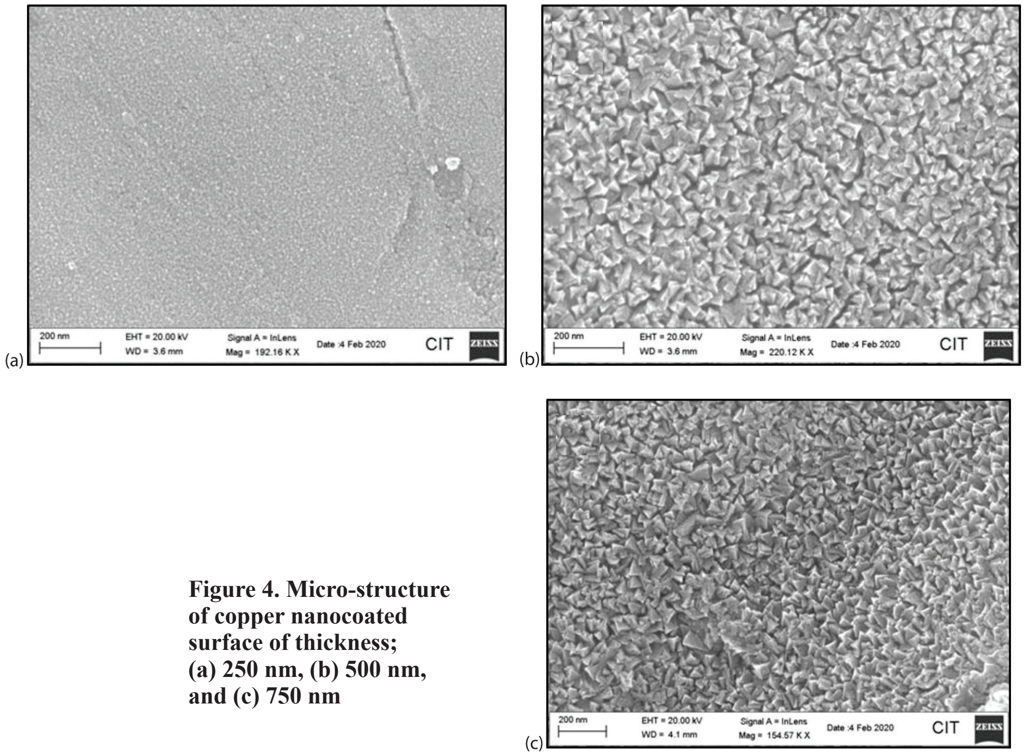

Figure 4. Micro-structure of copper nanocoated surface of thickness; (a) 250 nm, (b) 500 nm, and (c) 750 nm

The results of Panalytical-X'Pert X-ray diffraction unit shows that the presence of copper nanoparticles on the surface at all thickness ranges of coating. The peaks occurred in the graph as shown in fig. 5 evidenced that the copper nanoparticles spread over the surface exposed to heat transfer.

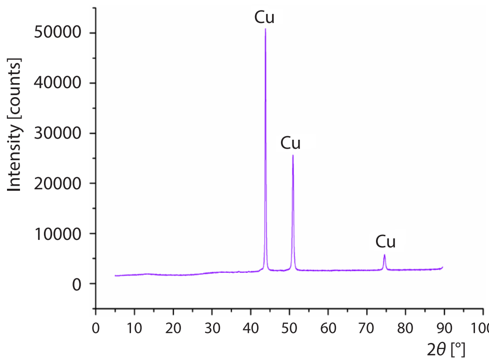

Figure 5. The XRD pattern of copper nanocoated surface

Analysis of nucleate boiling curve

In the present study, the CHF for bare copper substrate was found experimentally, and the experiment was conducted at least five times for the repeatability of results as shown in fig. 6.

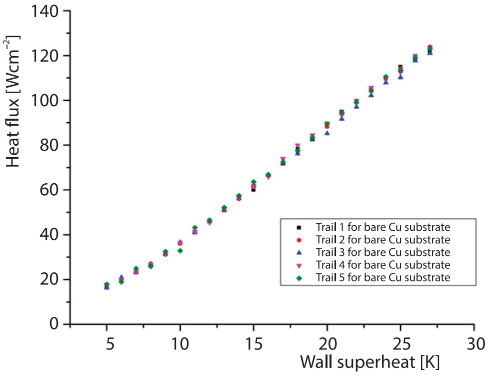

Figure 6. The CHF *vs.* wall superheat for plain copper surfaces

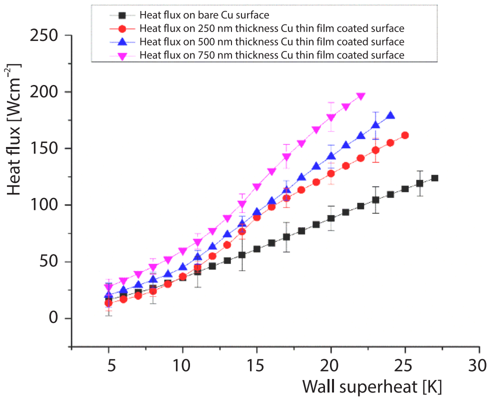

Figure 7. The CHF *vs.* wall superheat for copper nanocoated surfaces

The CHF of the plain copper surface was evidenced at 123.8 W/cm^2. The remarkable enhancement of CHF and HTC was witnessed in the pool boiling curve of copper nanocoated surfaces as shown in fig. 7 The surface morphology also has been modified and it results in the wettability enhancement. It is believed that the enhanced wettability was one of the reasons for the augmentation of CHF in pool boiling process.

The maximum decrement in the contact angle was witnessed in copper nanocoated surfaces in this study. The CHF of 250 nm thickness copper thin-film coated surfaces was evidenced at 161.5 W/cm^2. The enhancement was observed 30% higher in comparison with the plain copper surface. A plenty more nucleation sites were evidenced on the copper nanocoated surface as in comparison with the plain copper surface. A remarkable enhancement of CHF 44% for 500 nm thickness and 59% for 750 nm thickness was attained. The trend was similar for all the copper thin-film coated surfaces. This profound amelioration of CHF was achieved at low wall superheat in comparison with the plain copper surface. The trend of declining wall superheat at elevated CHF results in enhancing the safety of heat dissipation devices. The nucleation site density increases as the coating thickness increases and it tends to escalate the frequency of bubble formation in the nucleate boiling region.

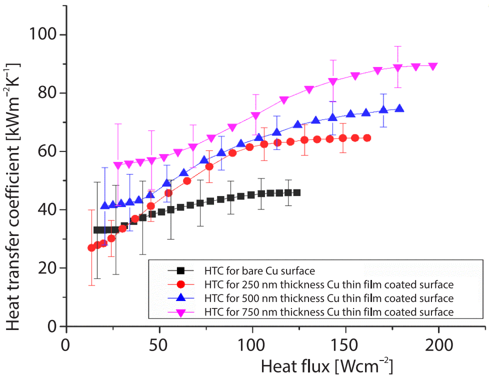

Figure 8. The HTC *vs.* heat flux for copper nanocoated surfaces

The HTC of the nucleate boiling was also enhanced while increasing the thickness of the coating as shown in fig. 8. The HTC enhancement was significantly high in the intermediate region of the nucleate boiling because of a larger portion of test surface exposed to deionised water. The enhancement of HTC has been evidenced in a rapid rate and attained a maximum of 99% for 750 nm thickness. At this stage of nucleate boiling, a large amount of bubbles was generated, detached and reached the top surface of the pool boiling liquid. The large amount of heat was transferred during this stage and enhances the boiling HTC. The rate of enhancement was reduced significantly in the later stages of nucleate boiling region. The significant reduction in HTC enhancement evidenced due to the coalescence of bubble has covered a large portion of the copper coated test surface. The heat dissipation rate was very low by convection mode because of the lower thermal conductivity of vapour blanket. A similar trend was observed in all the copper thin-film coated surfaces in this study. An augmentation in the HTC was at 41% and 62% for the thicknesses of 250 nm and 500 nm in comparison with the plain copper surface.

The CHF of 160 W/cm^2 was obtained for diamond mixture copper coated surfaces [43]. The uniform coating of copper nanoparticles was made on the test surface and the CHF of 142 W/cm^2 was obtained [44]. The CHF of copper aluminum composite coating [45] was reported as 185 W/cm^2. The CHF of modified copper surfaces such as inclined fins [46], re-entrant cavities [47], micro fins [48], porous channels [49], and pin fins [50] was reported approximately in the range from 122-167 W/cm^2. The CHF obtained in the present investigation for the thickness of 750 nm was achieved at 196 W/cm^2. However, the present results are significantly higher and comparatively better than the previous studies of copper nanostructure and modified copper test surfaces.

In this experimental investigation, the thickness of the coating is limited to nanoscale. At micro scale thickness, formation of tiny cavities in nanoscale is not possible. The nucleation process is only because of water entrapment in nanocavities. So, the nucleation site density is reduced significantly. The reduction in nucleation site density would diminish the heat transfer performance. Also, the coating technique, shape of the heat transfer surface and cost associated with coating limits the coating in very large-scale.

Analysis of wall superheat with bubble dynamics

The CHF occurrence at a minimal excessive temperature is another desirable factor for all heat transfer equipment handling with more than one phase of coolant. The present study reported the analysis of heat flux with the effect of wall superheat. The plain copper surface reached the burnout point at 27 K. The surface with copper nanocoating of the thickness 250 nm reached the burnout point at 25 K. But the remaining two surfaces of thicknesses 500 nm and 750 nm attained burnout point at a wall superheat of 24 K and 22 K, respectively. It has been identified that there is no significant variation in wall superheats for the thickness of 250 nm and 500 nm. But, the enhancement of CHF was significantly higher between these two surfaces, and also higher in 750 nm thickness surfaces. The formation of bubble is very high when the wall superheat attained approximately at 15 K for the surface with 250 nm thickness. The heat flux at 15 K of wall superheat was 89.2 W/cm^2 and heat dissipation rate was also high at this wall superheat.

At 15 K wall superheat, the boiling HTC was 59 kW/m^{2}K. The HTC obtained at 15 K was approximately 92% of the total HTC till the burnout point. The maximum HTC was obtained at 64.6 kW/m^{2}K for 250 nm thickness copper thin-film coated surface. The HTC obtained at burnout point for 500 nm thickness surfaces was found to be 74 kW/m^{2}K. The enhancement was 62% higher in comparison with the plain copper surface. The heat flux obtained at a wall superheat of 13 K was found to be 73.9 W/cm^2. The HTC achieved at burnout point of 750 nm thickness surfaces was found to be 89 kWm^{2}K. The heat dissipation rate was high upto the superheat temperature of 15 K for 750 nm thickness. Heat transfer rate was reduced significantly beyond this wall superheat condition due to the resistance offered by vapour blanket. But the CHF of 196 W/cm^2 is considerably higher than the CHF for the thicknesses of 250 nm and 500 nm surfaces and the plain copper surface.

Conclusions

The present study demonstrated the significant enhancement of CHF and HTC of copper nanocoated surfaces in nucleate boiling investigation. The profound enhancement was achieved by modifying the surface attributes, especially the surface roughness, wettability and the surface morphological properties. The copper nanocoating of thicknesses 250 nm, 500 nm, and 750 nm was made on the copper surface by DC sputtering technique. The effect of thin-film coating on surface has been explored clearly. The copper thin-film coated surfaces exhibited excellence in hydrophilic and improved surface roughness. The main outcomes of this experimental investigation are summarised as follows.

- The surface wettability of the copper nanocoated surfaces is improved as the thickness of the coating increased. The angle of contact made by water droplet on copper nanocoated surfaces was measured 58°, 50°, and 38° for an increasing order of the thicknesses. The smaller contact angle depicts more wettability and copper thin-film coated surfaces exhibited excellent hydrophillic nature at 750 nm thickness.
- The surface roughness of the copper nanocoated surfaces improved in nanoscale as the coating thickness was increased. A significant improvement in roughness of 0.143 μm was witnessed for 750 nm thickness.
- The maximum CHF enhancement was 59% for the thickness of 750 nm due to the excellent wetting characteristics of copper nanoparticles on the copper heater surface.
- The maximum HTC of 89 kW/m^{2}K was achieved for the thickness of 750 nm and 99% enhancement in HTC was evidenced.

Nomenclature

h – heat transfer coefficient
q – heat flux
k_{cu} – thermal conductivity of the copper
T_{sat} – liquid saturation temperature
T_w – surface temperature of the test block
T_1 – temperature for the position 1 from the top of the copper test surface
T_2 – temperature for the position 2 from the top of the copper test surface
T_3 – temperature for the position 3 from the top of the copper test surface
X_1 – distance from the top of the test surface to the thermocouple position 1
Δx – distance between the thermocouple position 1 and 2

Greek symbols

ω_q – uncertainty of heat flux
ω_k – uncertainty of thermal conductivity
ω_T – temperature uncertainty
ω_h – heat transfer coefficient uncertainty
$\omega_{\Delta x}$ – distance uncertainty

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