Experimental investigation on nucleate pool boiling heat transfer enhancement for nano-structured copper oxide coated heating surface

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Abstract. The present paper is based on experimental studies of augmentation of pool boiling heat transfer characteristics of unlike surfaces using water as a working fluid at atmospheric pressure. The test surfaces for the experiments include untreated, treated, copper oxide (CuO) thin film coated copper heating surfaces having coating thickness of 200 nm and 400 nm. The thin film coating is fabricated by sol-gel spin coating technique. The characterization of surfaces is done by considering wettability, surface roughness and topography study by the sessile droplet method, optical surface profile meter and X-ray diffraction [XRD]. The experiment is conducted in a closed boiling chamber and heat flux varied from 526.3 kW/m² to 2546.689 kW/ m². The augmentation of heat transfer coefficients is found more than 40.60% of the higher thickness of copper oxide thin film coated copper heating surfaces. This is happened due to enhanced wettability, roughness and increase in active nucleation site density.

1. Introduction
In today's technological advancement, high heat flux (HF) removal from electronic chips pose a great challenge for researcher. Among all the heat transfer mode boiling is the second highest mode after radiation. Boiling heat transfer (HT) enhancement is a burning topic related to removing high heat load. The pool boiling is very effective in nucleate boiling regime which is characterised by initiation of bubble from nucleation site and coalescence of vapour bubble to form vapour column. But this regime is limited by critical heat flux (CHF) as at this point considerable vapour is formed making it difficult to continuously wet the surface. Operation of several engineering systems are constrained by the CHF including atomic reactors, certain powerful cooling systems, and heat exchangers. So, the CHF value is raised by several methods to ensure safe operation of such engineering systems i.e., electronic devices. Amid various enhancement technique surface modification [1] is one of them and surface modification with micro/nano-structure surface is most favourable of them [2,3]. The micro/nano-structures not only modify the surface area but also increases the active cavity sites which further raise the heat transfer characteristics in nucleate boiling [4,5]. Implementing nanostructured surfaces, dramatically reduces...
boiling inception temperatures [7,9], capability of reducing the surface contact angle and rise in wettability in boiling incident [9, 14-17].

Wu et al. [2] reported that TiO$_2$ coating has greater impact on CHF (Critical Heat Flux) and HT than SiO$_2$ coating on copper surface with water and FC-72 as working fluid. They have shown that CHF enhanced 10.7% and 50.4% for SiO$_2$ and TiO$_2$ coated surface respectively for water and 13.9% and 38.2% SiO$_2$ and TiO$_2$ coated surface respectively for FC-72. They have concluded that improved hydrophilicity of TiO$_2$ over SiO$_2$ enhance boiling characteristics for TiO$_2$ coated surface for both the fluid. Chen et al. [3] incorporate EE (Electroless Etching) and electroplating technique to synthesize Si and Cu nanowire separately on Si substrate and showed enhancement of CHF value up to 200 W/cm$^2$. They attributed the enhanced boiling characteristics due to improved hydrophilicity and increase in active nucleation sites. Engineered surface having carbon nanotubes improves the CHF and heat transfer coefficient (HTC) with deionized (DI) water [6-8]. Demir et al. [14] reported improvement about 254% in HTC during boiling heat transfer using Si-nanorod structures which is done by a chemical etching process. Jo et al. [15] used an electroplating technique to grow a novel fractal-like Cu$_2$O nanostructures on NiCr wire. They changed the electroplating time to control the wettability and conclude that both hydrophobic and hydrophilic surface has advantage on electronics cooling as the former one reduces wire surface temperature and latter one improves CHF. Shi et al. [16] uses electroplating method on bare Cu surface to grow Cu nanowires of varying length 3-30 µm to study the heat transfer enhancement and found that as nanowire length increases enhancement increases attributed to enhanced wettability and increase in active nucleation site.

In this literature, thin film of various thickness of CuO ranging 200-400 nm is fabricated on copper substrate results the effect of coating depth and surface behaviour, wall superheat and HTC.

2. Preparation and Characterization of Test surfaces

2.1. Preparation of CuO nanostructure coated surface

To prepare the test surface Copper (C10200) is used having 99.99% purity. Four types of test surfaces are used: untreated (U-Cu), treated (T-Cu) and CuO thin film (TF) coated surface having thickness of 200 nm and 400 nm. The treated surface is finished by using emery grits, no. 2000, eliminating to entrap liquid by using 12% NaOH water solution, cleaning with water, and drying with natural air. Sol-Gel Spin Coating is used to deposit thin film on copper substrates as a nanostructure. The photographic views of test surface are shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** Views of different testing surfaces (a) U-Cu, (b) T-Cu, (c) 200 nm TF, (d) 400 nm TF

2.2. Measurement of contact angle of CuO nanostructure TF surface

The contact angles (CA) of all four surfaces are calculated by sessile drop technique and distilled is used as titres. To measure the CA, the average is taken for different testing surfaces. It is found that the uncertainties were in the range of ± 6°. Digital photos of testing surfaces with distilled water drops are shown in figure 2.
2.3. Measurement of surface roughness

To measure the roughness of a testing surfaces an Optical Profiler (Taylor Hobson Pvt. Ltd) is used. The roughness values of all four surfaces are collated in table 1 and 3D profiles are shown in figure 2. The crystalline nature of the CuO TF coating on copper substrate is noticed by XRD analysis shown in figure 3. The TF coating is found crystalline with the peak at $2\theta = 37^\circ$ relate to (112) Miller plane of CuO. The remaining projecting peaks are observed corresponding to $2\theta$ value are 43.2°, 50.3° and 73.9° correspond to the copper substrate.

3. Experimental Setup

3.1. Experimental installation details

The experimental setup (figure 4) is furnished with a boiling chamber which is manufactured by stainless steel (1) having dimensions of 150 mm in diameter and 305 mm in height, inside which boiling of liquid is done to study the boiling phenomena, i.e., to determine boiling aspect of the testing surface (2) and the working medium. The chamber is attached with a copper block for providing the heat flux to the boiling liquid. The cooling coil (3) is used for condensing the vapor to liquid. The pressure gauge is used (4) as a pressure measuring device, secondary heater (5) is used for heating the medium quickly, and viewing glasses (6) for observing the bubbles inside the boiling chamber. The heating block is connected in the bottom of the chamber (7) consisting of cartridge heater to provide HF and it is radially insulated (8) for reducing the heat exchange to the environment. For placing the testing specimen a space is made on the highest point of the heating block (2). Three T-type thermocouples (9), are utilized in the heating block to find the temperature at various stature and one is utilized inside the boiling chamber to quantify the temperature of saturated liquid. The chamber is wrapped with (8) glass wool and powder form of calcium silicate to prevent the heat loss with the environment through the wall. The Teflon sheet (10) is set between the specimen and the flange walls to evacuate the radial heat transfer from the testing surfaces. The HF is available through the primary cartridge heater (11). The valves (V1 and V2) is kept to regulate the liquid level and pressure accordingly. The charging gadget (12) is placed on the highest point of the chamber, for filling the working medium inside the chamber.

| Surface type      | Ra (µm) Before boiling | Ra (µm) After boiling | % change in roughness | Contact angle |
|-------------------|------------------------|-----------------------|-----------------------|---------------|
| Untreated         | 0.083                  | 0.072                 | 13.25                 | 88°           |
| Treated           | 0.064                  | 0.051                 | 20.31                 | 78°           |
| 200 nm CuO TF     | 0.247                  | 0.203                 | 17.81                 | 61°           |
| 400 nm CuO TF     | 0.352                  | 0.320                 | 9.09                  | 37°           |
Figure 3. XRD of 200 nm and 400 nm coated copper surface

Table 2. Photo images obtained by Optical surface profiler of testing and tested objects

| Heat transfer surfaces | Before boiling test run | After boiling test run |
|-----------------------|-------------------------|------------------------|
| U-Cu Surface          | ![Image](Image)          | ![Image](Image)        |
| T-Cu Surface          | ![Image](Image)          | ![Image](Image)        |
| 200 nm CuO coated surface | ![Image](Image)         | ![Image](Image)        |
400 nm CuO coated surface

3.2. Experimental analysis

To get the HF and surface temperature one dimensional Fourier law of heat conduction was utilized. Figure 5 delineates the relating resistance outline. The rate of heat exchange (Q) in segment (I), segment (x) and segment (y) are determined by utilizing the Fourier heat conduction equation 3.1, equation 3.2 and equation 3.3 individually.

\[
Q_I = \frac{k_{3x} A_{3x} X (T_3 - T_2)}{\Delta x_{3x}} \quad (3.1)
\]
\[
Q_x = \frac{k_{xy} A_{xy} X (T_x - T_y)}{\Delta x_{xy}} \quad (3.2)
\]
\[
Q_y = \frac{k_{ys} A_{ys} X (T_y - T_3)}{\Delta x_{ys}} \quad (3.3)
\]

Figure 4. Boiling experimental setup (a) Schematic diagram (b) Exploded view of heating block.
The equation from 3.1 to 3.3 was utilized to acquire the surface temperature of the copper substrate $T_S$ with the accompanying expression.

$$T_S = T_3 - \frac{VI}{K} \left( \frac{\Delta z_{3x}}{A_{3x}} + \frac{\Delta z_{3y}}{A_{3y}} \right) = T_3 - \frac{VI}{K} \delta \quad (3.4)$$

Where $T_S$ is the temperature estimated by thermocouples set at areas in the test segment of the copper heating rod.

The temperature probes were used to measure the bulk fluid temperature at any locations during the boiling tests. The temperature readings for a set of steady-state temperature data is used to evaluate the bulk fluid temperature ($T_L$). After determining the wall temperature and liquid temperature of the test segment tube, the average boiling heat transfer coefficient is assessed utilizing by Newton’s law of cooling.

$$h = \frac{q}{\Delta T} = \frac{q}{(T_S - T_L)} \quad (3.5)$$

3.3. Uncertainty analysis

Evaluation of uncertainty measurement of HF and HTC is very crucial in this sort of experiments. The error investigation for observing the results of the experimentations the measuring instruments uncertainty are determined utilizing Kline and McClintock [19] method. It is found that the uncertainties were in the range of ±3.38% for measuring instruments. Considering calibration error for thermocouples uncertainty of temperature is found to be ±0.05°C and for HTC is ± 4.39%.

4. Results and discussions

The boiling characteristics of four surfaces are experimentally investigated within nucleate boiling regime at atmospheric pressure. The tests are carried out by varying heat flux from 452.744 kW/m$^2$-2433.35 kW/m$^2$ by 10 min of time interval and then reduced back in a similar manner to check any hysteresis effect. Experimental findings of wall superheat, HF and HTC and boiling regimes are discussed in the subsequent section.

4.1. Heat Flux variation with Wall Superheat

Figure 6 is drawn between wall superheat and HF for four testing surfaces. From the nature of the curve it is seen that for CuO TF the graph is steeper towards ordinate. From the figure 6 the maximum reduction in wall superheat is found to be reduced from 22.317 K to 12.317 K for 400 nm coated surface as compared to treated surface. It seems that considered Nano composite structures of 400 nm shows higher active cavity on the surface which tends to improved wettability and nucleation sites.
4.2 Comparative study on wall superheat with earlier published data

Figure 7 is graphical representation between HF vs wall superheat for different testing surfaces of present work results with the data recorded by Huang et al. [17]. The comparative study shows significant improvement in HT for CuO coated TF surface as compared to other case. The variation of the data with literature is because of the different running states, different coating material, different coating depth and liquid used for boiling.

4.3 Variation of measured HTC with heat flux

Figure 8 has revealed that HTC is somewhat dependent on heat flux. From experimental result it has been detected that maximum improvement of HTC for 400 nm surface to be recorded as 81.18% and 40.59% as compared to U-Cu and T-Cu respectively at a HF of 2348.613 kW/m². The possible justification for the augmentation is due to escalation in number of site density [2,17].

5. Conclusions

In this experimental investigations, it is found that the pool boiling heat transfer enhancement is achieved by maintaining the surface properties by using different micro/nanoscale TF coating on testing surfaces. The TF coating is growth by sol-gel spin coating method which revealed hydrophilic nature. The nano-coating TF improves the boiling HTC than the untreated and treated surface. The prime outcomes of this study are given below.

a. The CuO thin film coating significantly affects the boiling HT and enhances the HTC. The maximum increment of HTC is found about 81.19% and 40.6% for the 400 nm CuO TF coated plane compared to untreated and treated surface respectively.
b. The wall incipience superheat is reduced in CuO coated thin film coated surfaces. The highest reduction of incipience wall superheat observed 40.6% for the 400 nm CuO coated surface compared to that of treated surface. This reduction in wall incipient superheat is due to large heat transfer from the surface.

c. The contact angles decrease from 61° to 37° with heightening coating thickness from 200 nm to 400 nm for CuO thin film coated surfaces. This is because as coating thickness increases the porosity of thin film also increases and assist in spreading the liquid into surface.

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