Experimental studies on nucleate pool boiling heat transfer enhancement for composite nano-structure coated copper heating surface

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Abstract. The present paper is based on experimental studies on nucleate pool boiling heat transfer enhancement of different surfaces using water as a base fluid at atmospheric pressure. The test surfaces for the experiments include untreated, treated, and treated with Aluminum-silver oxide composite thin film surfaces having nano-layer thickness of 180 nm and 260 nm. The thin films are prepared on copper substrate by electron beam evaporation technique. The characterization of the heated surfaces is done by using optical surface profilometer for surface roughness and sessile drop method for contact angle measurement. The experiment is conducted in a closed boiling chamber and the heat flux is varied from 141.524 - 1244.101 kW/m\textsuperscript{2} in time steps. The enhancement of heat transfer coefficient is found as 22.8\%, 17.27\% and 11.81\% from the 260 nm, 180 nm composite nanostructured coated and treated surfaces respectively compared to plain surface. Enhancement in nanostructured coated surfaces is found higher due to the capillary effect, increased wettability and high active nucleate site density and the increased rate of bubble frequency.

1. Introduction
In past few years, high heat flux removal from the high-performance electronic device encouraged the researchers to investigate into advance heat transfer techniques particularly in the sector of pool boiling and flow boiling. Among the regimes in pool boiling curve the Nucleate Boiling Heat Transfer (NBHT) is the most effective due to its ability to remove high heat load maintaining low surface temperature. From the various nucleate boiling enhancement techniques passive technique is one of the favourable techniques for augmentation of heat transfer as it does not require any external power input and modification is done through the fabrication of micro/nano-structures on tested surface. Passive heat transfer enhancement includes various methods includes surface modification by coating of metallic and non-metallic material, increasing surface roughness, extended surface, use of additives and surfactants, etc. In this literature, the E-Beam evaporation is used as a coating method for the heating surface as it promotes low material loss. Given the enormous number of articles and patents written on this subject, only a few representative and relevant studies are discussed here.
Yan et al. [1] used micro-nanoscale surface modification by depositing thin film of TiO\textsubscript{2} on the Cu substrate which increases the surface roughness. Boiling characteristics was also improved because of the increment in no of active nucleation site due to increase in surface roughness. Layer-by-layer technique is one of the desirable coating methods as it can be easily implemented and wide variety of material can be used. Forrest et al. [2] used this technique to obtain PAH (Poly allylamine hydrochloride)/SiO\textsubscript{2} thin film coating on nickel wires of different wettability. They observed both heat transfer coefficient (HTC) and critical heat flux (CHF) increased by two times than of bare wire. Seo et al. [3] experimentally investigated boiling performance by using FC-72 as a working fluid and hybrid film coated surface of graphene and CNTs deposited on an Indium Tin Oxide (ITO) as heated surface and promoted the inflation to the interconnected network of Single-Walled Carbon Nanotubes (SWCNTs) on graphene surface that made the connection to the disconnected lines. Yeom et al. [4] worked on TiO\textsubscript{2} and Ti nanoparticles for coating on copper substrate from 60-80 nm thickness using electrophoretic deposition technique to observe bubble dynamics and heat transfer analogy. Overall, the TiO\textsubscript{2}-nanoparticle coating provided better CHF value as compared to the Ti. Das et al. [5-8] has fabricated SiO\textsubscript{2} and TiO\textsubscript{2} TF coating on copper substrate using e-beam physical vapour deposition (E-beam PVD) process where 80% heat transfer improvement was recorded which is higher than TiO2 for 250 to 1000 nm of coating thickness. Carbon nanotubes (CNTs) are of great interest when it comes to pool boiling enhancement as it has better physical properties i.e. thermal, electrical and structural [9]. High thermal conductivity of CNTs (17 times higher than that of copper) promotes greater number of cold spots, better ability to collapse the vapor film and augmentation of surface area that in turn enhance HTC [10-13]. Apart from nanotubes nanowires, which are defined a nanoscale rods of large length to diameter ratio also used as a great tool for surface modification. Moreover, nanowire arrays modify wettability and contains a great number of cavities and pores that is potentially exploited by Lu et al. [14], Chen et al. [15], Shi et al. [16] to promote enhanced boiling performance. Zhang and Kim [17] used interconnected ANPS (Aluminium Nano-porous Surface) which shows enhancement of boiling heat transfer for water. They also observed that CHF augmentation was dominated by liquid spread and also induced in the porous structure. Vemuri et al. [18] investigated on Al surfaces by coating with Al\textsubscript{2}O\textsubscript{3} on FC-72 and they found about 30% decrease in incipience superheat over untreated Al surfaces. Lee et al. [19] examined the enhancement process by preparing the nanoporous composite surface by anodized method. Further they added that the electrolyte, potential, temperature and time duration are the important parameter in anodized method to increase the HTC of the oxide surface. The boiling wall superheat is found to be lower as compared to bare surface and the HTC is also higher than the plain bare surface. From the ample literature survey, it is observed that very few researches are concentrated towards composite material and E-beam thermal evaporation for nanostructured surfaces and coating methods.

2. Preparation and Characterization of Test surfaces
2.1. Preparation of Al-Ag oxide composite nanostructure coated surface
In this experiment, 99.99% pure copper (C10200) is used as a substrate. For the comparative study four types of test surfaces are prepared: untreated (U-Cu), treated (T-Cu) and Al-Ag oxide nanostructure coated thin film (TF). An e-beam evaporation system (15F6, HHV India) is used to deposit highly pure Al\textsubscript{2}O\textsubscript{3} and Ag\textsubscript{2}O (99.999 %, MTI, USA) composite nanostructure on 15 mm diameter copper substrate using at a vacuum pressure of 2 \times 10\textsuperscript{-5} mbar. Thin film growth rate of 0.12 nm/s is employed for all four surfaces. Al\textsubscript{2}O\textsubscript{3}-Ag\textsubscript{2}O composite atoms are deposited at an incidence angle of 90\degree. The untreated, treated and treated with 180 nm and 260 nm Al-Ag oxide nanostructure surfaces are shown in figure 1.
2.2. Contact angle measurement of Al-Ag oxide nanostructure coating surface
Contact angle measurement of four surfaces are done by using sessile drop method and distilled water is used as titres. The average value is taken for contact angle measured three times for each surface. It is found that the uncertainties were in the range of ±6°. Digital photos of thin film coated surfaces and distilled water drops on these surfaces are taken in natural light are shown in figure 2.

2.3. Measurement of surface roughness
To measure the surface 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 table 2. The crystalline nature of the Al-Ag oxide TF coating on copper substrate is observed by XRD analysis shown in figure 3. The TF coating is found crystalline with the peak at 2θ = 37.8° relate to (111) Miller plane of Al2O3. The remaining three projecting peaks are observed corresponding to 2θ value are 43.2°, 64.3° and 73.9° correspond to the copper substrate.

3. Experimental Setup
3.1. Experimental installation details
The experimental setup as shown in figure 4(a-b) is consists of a) boiling chamber made of stainless-steel of dimensions dia. 105 mm and height 305 mm, b) copper heating block, c) heating surface, d) insulating material (Teflon and glasswool), e) cooling coil, f) primary heater (4 cartridge heater), g) secondary heater (cartridge heater), h) thermocouple (K-type), i) viewing glass, j) pressure gauge. Boiling vessel is insulated using polyurethane foam and then glasswool of each having thickness of 25 mm. Copper sample is placed in a slot on the top of the heating block and four cartridge heaters of 250 W are installed in the copper heating block. To ensure prevention of radial heat loss from heating block, the block assembly is inserted into a Teflon block (see figure 4b). Also, a Teflon sheet is wrapped around the heated sample and the flange wall to minimise radial heat loss. The primary heater is connected to a dimmerstat which is in connection with a 220 V power supply. The secondary heater is placed in the boiling vessel suspended from the top fully submerged in liquid to increase the water temperature quickly. Three K-type thermocouple are inserted in the slot in copper heating block in regular interval.
and another one is installed inside the boiling chamber to record the temperature of liquid during boiling. Two valves (V1 and V2) were used to regulate the liquid level and pressure.

**Table 1.** Surface roughness and contact angle value of testing surfaces

| Surface type          | Ra (µm) Before boiling | Ra (µm) After boiling | % change in roughness | Contact angle |
|-----------------------|------------------------|-----------------------|-----------------------|---------------|
| Untreated             | 0.076                  | 0.056                 | 26.31                 | 58°           |
| Treated               | 0.05                   | 0.03                  | 20                    | 55°           |
| 180nm Ag-Al TF        | 0.08                   | 0.063                 | 21.25                 | 48°           |
| 260nm Ag-Al TF        | 0.12                   | 0.092                 | 23.3                  | 42°           |

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

| Heat Transfer surfaces | Before boiling test run | After boiling test run |
|------------------------|-------------------------|------------------------|
| U-Cu Surface           | ![3D Surface](image)   | ![3D Surface](image)   |
| T-Cu Surface           | ![3D Surface](image)   | ![3D Surface](image)   |
| 180 nm Al-Ag Oxide coated surface | ![3D Surface](image)   | ![3D Surface](image)   |
| 260 nm Al-Ag Oxide coated surface | ![3D Surface](image)   | ![3D Surface](image)   |
Figure 3. XRD pattern thin film nano structure coated surface.

Figure 4. Boiling experimental setup (a) Schematic diagram (b) Resistance diagram

3.2. Uncertainty analysis
The error analysis for observing the outcomes of the experimentations the measuring instruments uncertainty are calculated using Kline and McClintock [21] method. It is found that the uncertainties were in the range of ±3.5% for measuring instruments. Considering calibration error for thermocouples uncertainty of temperature is found to be ±0.05°C and for heat transfer coefficient is ± 6.31%.

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 141.5 – 1244 kW/m² by 10 min of time interval and then reduced back in a similar manner. Experimental findings of wall superheat, heat flux and heat transfer coefficient and boiling regimes are discussed in the subsequent section.

4.1. Heat Flux variation with Wall Superheat
Figure 5 is drawn between wall superheat and heat flux for four testing surfaces. The nature of the curve and data set lies in the nucleate boiling region and also wall superheat is recorded in the range of 4 - 11.5°C. From the figure 5 the maximum reduction in wall superheat is found to be reduced by 18.56% for 260 nm coated surface at heat flux near to 1244 kW/m². It seems that considered Nano composite structures of 260 nm shows higher active cavity on the surface which tends to improved wettability and nucleation sites.
Figure 5. Boiling curve based on heat flux data with wall superheat of all testing surfaces.

Figure 6. Comparative study of current findings with previous published findings.

4.2. **Comparative study on wall superheat with earlier published data**

Figure 6 is graphical representation between heat flux vs wall superheat for different heat transfer surfaces of present experimental results with the data reported by Tang et al. [20] and Shi et al. [16]. The comparative study shows that the considered Nano composite material enhanced heat transfer compared to other two cases by 87.39% [20] and 63.95% [16]. The composite of Ag$_2$O-Al$_2$O$_3$ on copper surfaces increases the active nucleation sites due to which more enhancement is observed for the considered materials.

4.3. **Variation of measured HTC with heat flux**

Figure 7 has revealed that HTC is somewhat dependent on heat flux. From experimental result it has been detected that there is an improvement in HTC on TF coated surface by 22.8%, 17.27% and 11.81% enhancement in HTC are recorded for 260 nm and 180 nm coated surface in contrast to bare surface at heat flux (1244 kW/m$^2$). The possible justification for the augmentation is due to escalation in number of site density which is an agreement with Vemuri et al. [18].

Figure 7. Effect of heat flux on boiling curve with heat transfer coefficient.

4.4. **Bubble behaviour**

From figure 8 (a-c) it is observed that for all tested surfaces the bubble diameter increases with increase in heat flux attributed to increased bubble velocity. In figure 8 (b-c) it is observed that for 260 nm of nano-composite structured surface shows smaller bubble dia. at 864 kW/m$^2$ of heat flux compared to 180 nm test surface at 0.945 MW/m$^2$ also higher nucleation sites are observed for same case. It seems that the effect of coating thickness and nano composite material properties are affecting on the bubble phenomenon for heat transfer augmentation in NBHT region. The bubble Dia. of 0.62 mm is observed.
at 864 kW/m² heat flux for 260 nm testing surface. Bubble velocity of 0.105 m/s observed for 260 nm of testing surface than the other cases, it is due the effect of thermo-physical properties of Nano composite Al-Ag materials coated on copper surfaces.

(a) Treated, 120 kW/m²  
(b) 260 nm, 864 kW/m²  
(c) 180 nm, 935 kW/m²

Figure 8. (a- c) Photo images of the bubbles of tested surface with variation in the heat flux (kW/m²)

5. Conclusions
In this experimental investigations, it is found that improvement in pool boiling heat transfer is attained by sustaining the surface properties of TF coating on heating surfaces. The TF coating is applied by e-beam evaporation method which showed hydrophilic surfaces. The nano-coating is the prime factor in enhancing pool boiling characteristics and its effect on the HTC. This enhancement is achieved due to the lower contact angles. From obtained results it is found that contact angle is reduced with increasing coating thickness. The main findings from this experimentation are summarized below.

a) A maximum of 22.8% improvement is observed for Al-Ag oxide composite nano-coated (260 nm) surface than the bare Copper surface at reduced heat fluxes about 1244.101 kW/m² with an uncertainty 6.3%.

b) At medium heat fluxes about 141.524 kW/m² a maximum of 17.27% enhancement is observed for Al-Ag oxide composite nano-coated (180 nm) surface from the bare Copper surface with an uncertainty 6.08%.

c) At reduced heat fluxes about 1244.101 kW/m², 11.81% of maximum enhancement is recorded for treated surface from the plain surface with an uncertainty 5.9%.

d) The contact angle decreases from 48° to 42° as the coating thickness increases from 180 nm to 260 nm for nano-particle coated TF surfaces. The result support the dependancy of the contact angle reduction on the coating thickness increase which yields a high HTC.

e) The bubble dynamics results reveal the heat transfer enhancement for the 260 nm of nano coating test surface than other surfaces. It is due to the surface getting more hydrophilic with the increase in thickness of TF and the increased number of active cavities which leads to raised HTC.

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