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Enhanced Pool Boiling Heat Transfer on Aluminum Substrates with Silver Nanoparticles and Graphene Oxide Coatings

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Abstract

Surface property enhancement and boiling heat transfer characterization can be achieved through the use of nanoparticle coatings on substrates, such as graphene oxide (GO) and silver nanoparticles (AgNPs). The current investigation's primary goal is to learn how the nanocomposite coating affects the efficiency of boiling heat transmission in pools. By manipulating the nanomaterial concentration, the dip coating approach coats aluminum substrates with AgNPs + GO nanoparticles. Coating wettability behavior, surface roughness, and morphological analysis are also recorded. Coating samples with AgNPs + GO makes them more surface rough, and the results reveal that these samples are extremely hydrophilic. If compared to coated sample to the uncoated, the critical heat flow increases by 145.76% and the heat transfer coefficient by 259.08% were observed. Additionally, the computed bubble diameter, departure frequency, and site density were shown.

Keywords

Pool boiling, Silver nanoparticles, Surface roughness, Nanomaterials, Heat transfer

Introduction

Improving boiling heat transfer efficiency, which includes improvements of critical heat flux and heat transfer coefficient can yield multiple benefits in terms of efficiency, safety, and cost reduction associated with heat transfer systems [1]. Pool boiling heat transfer was extensively analyzed for its diverse industrial applications, such as heat exchangers, air conditioning systems, domestic refrigerators, and heat pipes [2]. Several investigations have explored various test fluids, including water, nanofluids, refrigerant and dielectric fluids, in this field [3]. However, altering the working fluid may not be feasible in steam power generation and water desalination. Therefore, surface modification is crucial to improving boiling heat transfer in most applications. Surface modification techniques were used to improve pool boiling performance by increasing heat transfer coefficient (HTC), reducing onset boiling, and promoting nucleation of vapor bubbles [4]. Researchers have used several surface modification techniques, like surface roughening and texturing, micro and nanostructures and surface coatings [5].

Coatings with high thermal conductivities, such as graphene and AgNPs, are promising for improving pool boiling performance due to their unique properties, like thermal conductivity, which is excellent, mechanical strength is great and a large surface area to volume ratio. Researchers investigated the effect of these coatings on pool boiling. In a study, the impact of a graphene coated surface on pool boiling was analyzed. They noted that the thickness of the graphene coating has a prominent impact on the performance of heat transfer [6]. Specifically, thinner coatings led to superior performance. In a recent study, authors used a model for an aluminum network to estimate the heat transfer coefficient at boiling of graphene coated aluminum surface at varying thicknesses. The study has involved characterizing the coated surface, conducting experiments to measure heat flux, HTC, and wall superheat, and comparing the results to previously established empirical correlations [7, 8]. Researchers [9, 10] conducted a study in which they applied GO nanocoating to a plain aluminum surface. The researchers [11] observed gradual increase in both critical heat flux (CHF) and maximum HTC on GO nanocoated surface compared to aluminum surface. Specifically, the GO nanocoating do enhanced CHF by 78% and HTC by 41%. These findings suggest that GO nano coatings may have potential for improving heat transfer in various applications. According to authors [12, 13], when smooth aluminum substrates were coated with graphene, there was an increase in the receding contact angle while the advancing contact angle remained largely unaffected. According to a study by researchers [14, 15], thermal conductivity and boiling heat transfer capabilities of substrates were examined in relation to the effects of adding single-layer graphene. The research [16, 17] concentrated on aluminum, nickel, platinum, and silicon's 100, 110, and 111 planes, which were typically employed in heat transfer and were compatible with graphene. Through molecular dynamics simulations, the vibrational density of state data was analyzed, and nanoscale boiling curves were generated. The findings demonstrate that the incorporation of single-layer graphene significantly enhances the composite substrate's overall thermal conductivity, with increases ranging from 1 to 2 orders of magnitude [18].

Researchers [19] prepared a coated boiling surface using multiwalled AgNPs (MWAgNPs). It was observed that double-layer coating was more efficient compared to single layer coating, for the enhancement. Researchers carried out a study to determine the effects of various AgNPs structures and functional groups on the HTC and the CHF of boiling pools. Their findings indicate that the use of functionalized AgNPs can lead to a significant improvement in both HTC and CHF. Furthermore, the size of the AgNPs was found to have an impact on their thermal performance. Researchers conducted an investigation on saturated pool boiling to observe the impact of the orientation of the fully AgNPs coated silicon surface and the surface with an interlaced pattern of AgNPs. It was observed that an orientation angle of 90° provides better heat transfer co-efficient. Authors investigated the impact of MWAgNPs content on aluminum foam in boiling heat transfer. It was observed that HTC and CHF improved by 3.41 times and 2.50 times, respectively, for coated samples. The properties of the pool boiling were experimentally observed on aluminum surfaces that had been bare, sandblasted, and covered with AgNPs by authors. They discovered that an AgNPs coated aluminum surface showed a 38% improvement in CHF.

It is observed from the above discussion that GO and MWAgNPs have excellent properties for boiling heat transfer improvement. However, composite coatings are also beneficial for creating more nucleation sites. Authors used two different types of composite coating. Composite coatings composed of aluminum, AgNPs, and ceramic particles such as silicon carbide and aluminum nitride were fabricated, which create random cavities. It was observed that the addition of ceramic particles with aluminum-AgNPs increases the co-efficient of boiling heat transfer. Researchers used aluminum-alumina nanocomposite coating on aluminum surface. To develop the coating electrochemical deposition was used. The pool boiling result shows that there was an enhancement in CHF of 68% where 408% in nucleate boiling heat transfer coefficient.

Mixing AgNPs and GO in coatings has been motivated by the desire to overcome the limitations of conventional GO/rGO coatings like weak bond strength between substrate and coatings, wettability and surface roughness [20]. Previous work has shown that AgNPs alone can create nanoporous coatings with tunable wettability [21]. However, the addition of GO to AgNPs-reinforced coatings offers several advantages such as improvement of wear performance by reducing the formation of cracks, ensuring uniform AgNPs distribution, and enhancing adhesion to the substrate [22]. Therefore, the motivation to mix AgNPs and GO in coatings is to achieve enhanced properties and overcome the limitations of conventional coatings [23].

Very few works are done for the enhancement of heat transfer to generate the microporous surface using the hybrid method. In this present work, GO and MWAgNPs nanocomposite coatings on aluminum surface are prepared through the sol-gel dip coating method. Among the various techniques available for coating, the sol-gel dip coating technique is more convenient and economical. Researchers examined how the nanocomposite covering affected the efficiency of heat transfer during boiling in pools.

Methodology

Preparation of nanoparticle

Two different types of nanomaterials, namely AgNPs and GO are used for the preparation of the hybrid nanomaterial. Steps involved in preparing the nanomaterial are: first, AgNPs and GO are mixed in a 2:1 ratio in a solution consisting of deionized (DI) water, $AlSO_4$ (0.5 M) and H_2SO_4 (0.2 M) with the help of a probe sonicator. Secondly, to obtain the powdered form of aluminum based AgNPs + GO, nanomaterial solution is kept inside an oven at a temperature of 150 °C for 24 h. Now, prepared nanomaterial in powdered form containing AgNPs and GO is used to prepare nanofluid.

Preparation of nanofluid

DI water is utilized as a base fluid for hybrid nanofluids making. Four different concentrations (w/v) of nanofluid

– 0.3%, 0.6%, 0.9%, and 1.2% are prepared. So, a colloidal solution is obtained after completing the mixing process using an ultrasonic probe sonicator. Colloidal solution of nanofluid is stable as observed for 24 h. Now, dip coating method is applied to prepare nanocomposite coating of AgNPs and GO on basic aluminum surface preparation.

Cleaning of the bare aluminum

Aluminum surfaces have a diameter and thickness of 20 mm and 1 mm, respectively, and are cut with the help of wire electrical discharge machining. Impurities are removed from the surface of basic aluminum using sandpaper of #1000 and #2000 grit. After that, surfaces are washed for 15 min each with distilled water, acetone and ethanol under ultrasonic cleaning, and then they are dried with hot air.

Dip coating technique

The cleaned substrate is dipped into the hybrid nanofluid at a steady speed. Depending on the type of material, a step called "pre-treatment" would come before this step. When a certain amount of time has passed, the substrate starts to be taken out of the fluid. While the base is being taken away, the thin film coating starts to form on it. The base is pulled out of the nanofluid at a certain speed. As it pulls slowly, it is observed that the coating layer is getting thinner. In this present study, withdrawal speed is maintained at 100 mm/s. After it is removed from the solution, the solvent starts to evaporate from the surface of the substrate, leaving a thin layer.

The range of dip coaters is split in two. On one side, there are dip coaters that don't move horizontally and are best used with a single vessel. On the other side, there are dip coaters that do move horizontally and can be used to dip more than one vessel at a time. There are very few studies that change things like temperature, dipping time, removal, clamp holding time, rpm, and concentration to check the coating layer. In the present work on coating, the dipping time is 120 sec, while the magnetic stirrer speed is fixed at 300 rpm. Before the dip coating process nanofluid is mixed in the probe sonicator.

Pool boiling experimental procedure

Figure 1 presents a schematic view of dip coating machine. The boiling chamber diagram is presented in figure 2. The boiling region is enclosed using a polycarbonate glass, and the boiling test was carried out utilizing DI water, which worked as a boiling fluid. The experiment was performed at atmospheric pressure. The boiling chamber is covered with polycarbonate glass and made of Teflon. It has dimensions of 40 mm and 200 mm in depth and diameter, respectively. To provide the necessary heat, a cartridge heater (400 W) is placed at the base of a heating block, which is rectangular in shape. Glass wool insulation is used to keep the aluminum block from losing too much heat. The high-conductivity Omega OT-201-2 thermal paste was used to attach the test sample to the top of the heating block. To protect against heat from the top of the aluminum block, a silica gel was used to cover it. The heating block's surface temperature was measured by three K-type thermocouples shown in figure 3. Those thermocouples provide temperature measurements to a data collection system. A PID controller is connected to a 150 W

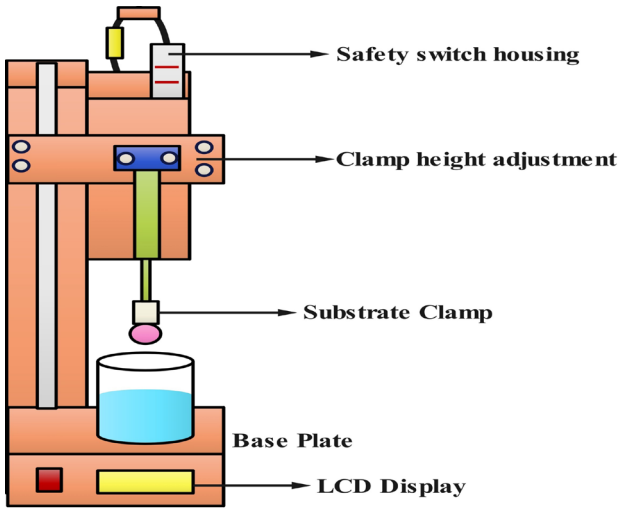


Figure 1: Schematic view of dip coating machine.

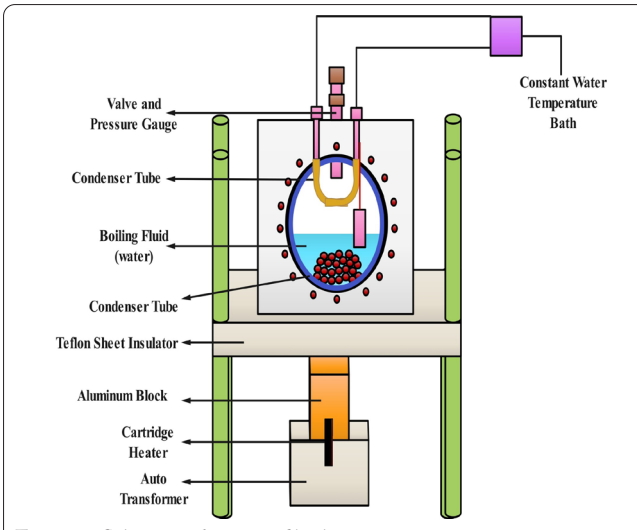


Figure 2: Schematic diagram of boiling setup.

cartridge heater that is placed inside the boiling chamber to keep the working fluid at saturation. The movement of bubbles is visualized using a high-speed camera. A water bath with a steady temperature is used to get rid of the often-formed

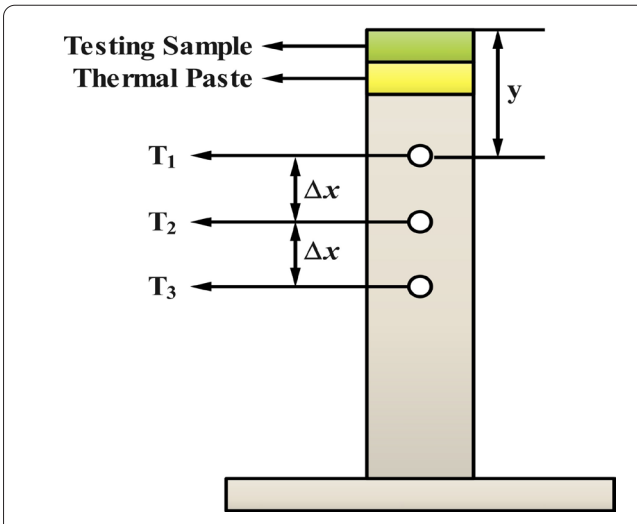


Figure 3: Thermo couple positions on aluminum block.

vapor inside the boiling chamber. This helps keep the fluid at the same level.

Initially, the boiling chamber undergoes a process to eliminate all non-condensable gases. This is done by boiling 200 ml of DI water in the chamber for 3 h straight at saturation temperature. So that the situation stays stable, and the boiling process is lengthened by 3 - 4 h. When temperature changes by 0.2 °C every 3 min, it is considered to be steady state. At this point, thermocouples (T1, T2, and T3) readings were recorded. Once the first heat flux was stabilized, a small amount of power is added to the test sample, allowing the system to settle down again. When the next heat flux enters a steady state, usually 40 to 45 min after the first heat flux was recorded, the temperatures are taken. This process was repeated, and the amount of heat added is slowly increased until the surface hits the CHF after another 40 to 45 min of recording each heat flux. As the system gets closer to CHF, temperatures T1, T2, and T3 change quickly. At this point, the power is suddenly cut off to the object being tested.

Equation 1 is used to calculate heat flux using the measured temperatures at different times, where dT is the change in temperature, which can be found in equation 2.

$$q" = -k_{cu}\frac{dT}{dx} \tag{1}$$

$$\frac{dT}{dx} = \frac{3T_1 - 4T_2 + T_3}{2x} \tag{2}$$

As a result, equation 1 and equation 2 are used to compute the rate of heat transfer at the boiling surface for each degree of heat intake. Then, using equation 3, each level's boiling surface temperature is determined.

$$T_S = T_1 - \frac{q^* .y}{k_{cu}} \tag{3}$$

Equation 4 is used to obtain the boiling heat transfer coefficient (BHTC).

$$h = \frac{q"}{T_S - T_f} \tag{4}$$

Analysis of uncertainty

The commonly used Kline and McClintock approach is used to calculate the uncertainty linked to various sorts of parameters. In order to determine the CHF uncertainty, heating surface temperature, and BHTC, respectively, equation 5 to equation 7 are employed.

$$\frac{\omega q}{q} = \left[\left(\frac{3.\omega_{T_1}}{3T_1 - 4T_2 + T_3}\right)^2 + \left(\frac{4.\omega_{T_2}}{3T_1 - 4T_2 + T_3}\right)^2 + \left(\frac{\omega_{T_3}}{3T_1 - 4T_2 + T_3}\right)^2 + \left(\frac{\omega_x}{x}\right)^2\right] \tag{5}$$

$$\frac{\omega_{T_S}}{T} = \left[\left(\frac{K_{Cu}\omega_{T_1}}{K_{Cu}T_1 - q.y}\right)^2 + \left(\frac{y\omega_q}{K_{Cu}T_1 - q.y}\right)^2 + \left(\frac{q.\omega_y}{K_{Cu}T_1 - q.y}\right)^2\right]^{\frac{1}{2}} \tag{6}$$

$$\frac{\omega h}{h} = \left[\left(\frac{\omega_q}{q}\right)^2 + \left(\frac{\omega_{T_S}}{T_S - T_f}\right)^2\right]^{\frac{1}{2}} \tag{7}$$

In the above equation, ω_y and ω_x represent, respectively, the uncertainty in computing the gap among first thermocouple from test sample and the distance between the thermocouples. When calculating those distances from numerous physical measurements, a 5% inaccuracy is discovered. Again, there is a 1.2% margin of error when recording different temperatures using different thermocouples at different heat fluxes.

Equation 5 provides the uncertainty of the heat flux, which is 12.14%. The uncertainty related to boiling surface temperature and HTC is 11.20% and 10.31%, respectively.

Results and Discussion

Contact angle (CA) and surface roughness (Ra)

Surface wettability is the surface's ability to attract and hold onto water molecules, which can improve heat transfer performance [24], and it can be quantified by CA measurement using a Goniometer. CA of the bare aluminum surface has been found at 73° which is hydrophilic in nature. The CA of coated surfaces was found below 20° which is super hydrophilic in nature. This means that the nanocomposite coating increases the surface's ability to attract and hold onto water molecules, which can improve heat transfer performance. It is observed that as the concentration of the hybrid nanofluid increased, the wettability of the surface increased. This means that the nanocomposite coating increases the surface's ability to attract and hold onto water molecules, which can improve heat transfer performance [25]. A captured image of CA of the coated samples, and values of CA is mentioned in table 1 [26]. Another significant characteristic that may impact heat transfer is Ra. An instrument for assessing Ra is used to measure the roughness of all the surfaces, including the basic aluminum and all generated samples. The average roughness value (Ra) is checked for sample 1 and sample 4, Ra was found 5.66 µm, 12.72 µm, respectively. From table 1, it can be seen that as concentration of the hybrid nanomaterial is increased average Ra also increases.

Table 1: Measured value of CA and Ra.

S. No.	Parameters	Bare Al	S1	S2	S3	S4
1	CA (°)	73	18	14	11	5
2	Average Ra (µm)	0.39	5.66	6.78	9.21	12.72

Validation of experimental set up

The validity of the experiment is demonstrated by comparing the observed data of the pool boiling on the bare Al surface with the widely known correlation of Rohsenow and other scholarly works. Figure 4 shows how the results compare to each other. Theoretical and experimental results are pretty close to each other. The correlation of Rohsenow is [26]:

$$h = \mu_L.h_{lv}.\left[\frac{g.(\rho_L - \rho_V)}{\sigma}\right]^{0.5}.\left(\frac{c_p}{c_{sf}.h_{lv}.\mathrm{P_r}}\right)^3.(T_s - T_f)^2 \tag{8}$$

In the above equation, C_{sf} is set to 0.0165.

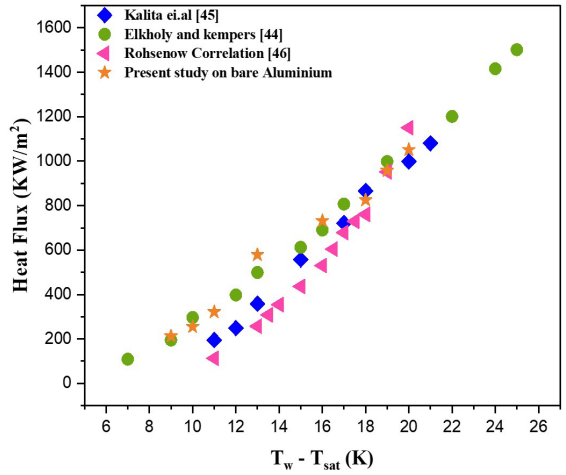


Figure 4: Experimental validation with published results.

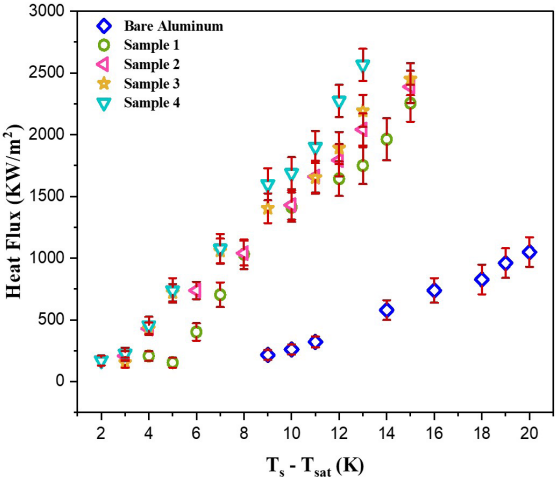


Figure 6: Boiling curve of all the sample.

Experimental pool boiling results

Comparison of AgNPs, GO and AgNPs + GO coating

To fairly access the influence of AgNPs + GO coating on pool boiling, it is essential to separately evaluate the performance of AgNPs and GO coating on pool boiling. Figure 5 shows the boiling curve for various types of coating. The CHF of bare aluminum surface is observed to be 1037.4 KW/m² and BHTC is 51.60 kW/m²K, which is the same as Zuber's correlation. All the coated samples show better CHF compared to bare aluminum. The CHF of AgNPs and GO coated samples are observed to be 1779.6 kW/m²K and 1590.11 kW/m²K, respectively. It is also observed that AgNPs-GO coated surface has a higher critical heat flux compared to other coated surfaces.

Pool boiling results of AgNPs-GO coating surface

To investigate the pool boiling heat transfer behaviour of bare aluminum and AgNPs-GO coated aluminum surface, they are tested using DI water as the working fluid. Figure 6 shows the variation of wall superheat with heat flux. Fig. 7 shows the variation of the BHTC with respect to heat flux. It is noticed from figure 6 that the boiling aluminum is shifted toward the left for sample 1 to 4, which implies wall superheat is lower in the same heat flux.

In general, it talks about the improvement of the boiling heat transfer performance of the coated samples. Sample 4 exhibits the highest CHF and BHTC value of 2549.6 kW/m² and 185.29 kW/m²K, respectively, which is 145.76% for CHF and 259.08% for BHTC, more compared to the uncoated surface. In this present investigation, the concentration of the samples varies from 0.3% to 1.0 % (from sample 1 to sample 4). In sample 1, CHF and BHTC values increased 115.77% and 177.71% compared to the uncoated surface. CHF and BHTC are observed 129.19% and 194.74%, respectively, for sample 2. Sample 3 enhanced significant amount of CHF and BHTC, 134.28% and 205.05%, respectively, compared to uncoated surface. The reason behind this improvement is that the AgNPs-GO coating increase Ra and makes the surface super hydrophilic in nature (Figure 7). Table 2 shows the overall obtained values of all samples.

Bubble visualization and analysis

Figure 8 shows the variation of the nucleation site with wall superheat. It is observed that at low wall super heat bubble

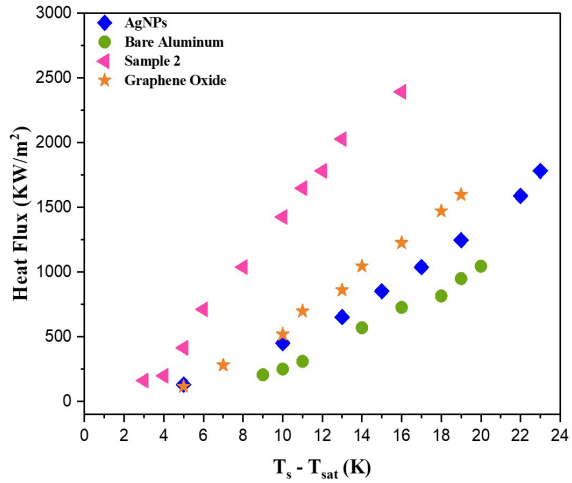


Figure 5: Variation of heat flux with wall superheat temperature.

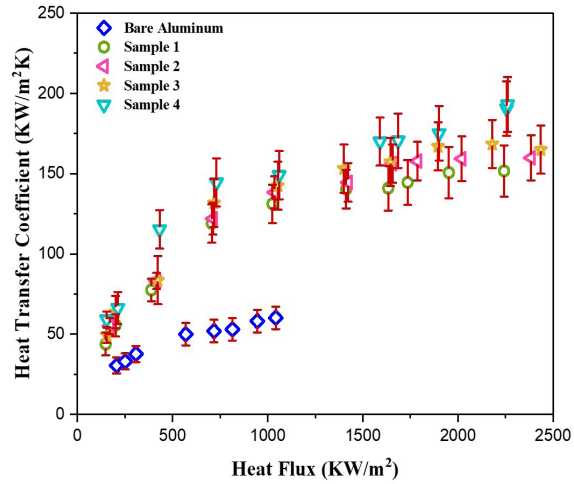


Figure 7: Changes in BHTC with heat flux for all samples.

Table 2: CHF and BHTC of coated and uncoated surfaces.

Samples	Ra (μm)	CA (°)	CHF (KW/m²)	BHTC (KW/m²K)
Bare aluminum	0.39	73	1037.4	51.60
Sample 1	5.66	18	2238.4	143.30
Sample 2	6.78	14	2377.62	152.09
Sample 3	9.21	11	2430.42	157.38
Sample 4	12.72	5	2549.6	185.29

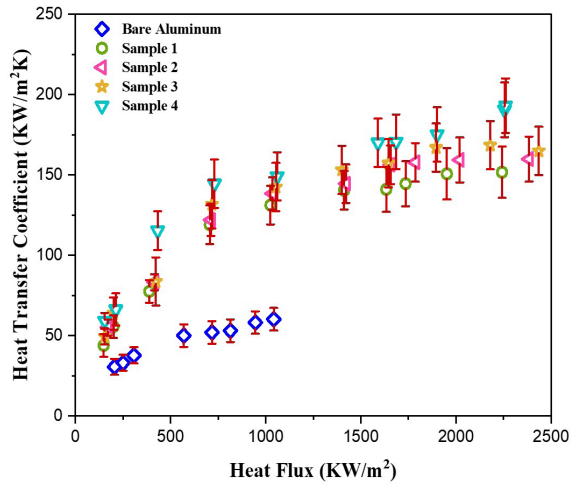


Figure 8: Nucleation sites variation with wall superheat.

site density is much higher for coated samples compared to aluminum. It is also visible that as the concentration of the samples varies from 0.3% to 1.0%, there is an increase in nucleation site density. An uncertainty of 25% was found in the calculation of nucleation sites density. The enhanced nucleation site density resulting from the coating can be explained by several factors. Firstly, the increased Ra introduced by the AgNPs and GO provides more favorable sites for bubble nucleation. The irregularities and microstructures on the coated surface create localized variations in surface energy, promoting the initiation of nucleation. Secondly, the presence of AgNPs within the coating introduces nanoscale structures that act as additional nucleation sites. The unique geometry and high surface area of AgNPs facilitate the formation of small vapor pockets and the subsequent growth of bubbles. The higher nucleation site density on the coated surfaces leads to improved boiling performance by promoting more efficient heat transfer.

The analysis of the bubble diameter that is departed from the coated aluminum surfaces, revealed a noticeable reduction compared to uncoated surfaces. Open-source software, Image J is used to calculate the bubbles diameter. An error of 13% calculated while finding the bubbles diameter.

In figure 9, variations in bubbles diameter are shown with wall superheats. In sample 4, it is observed that the diameter of the bubbles is very small compared to all the coated and uncoated surfaces. As the concentration of hybrid nanofluid increases from 0.3% to 1.2%, departed bubbles diameter decreases. The smaller bubble departure diameter indicates a higher bubble detachment frequency, which enhances heat transfer and leads to improved CHF and HTC. An uncertainty of 12% is found in the calculation of bubbles departure frequency. In figure 10, the frequency of all the samples is shown at the different wall superheat. It can be seen that the frequency of sample 4 has more compared to the other samples at different wall super heat.

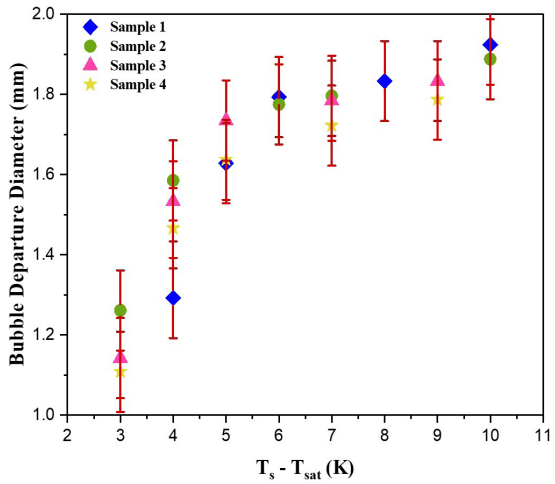


Figure 9: Bubble Dd variation with wall superheat.

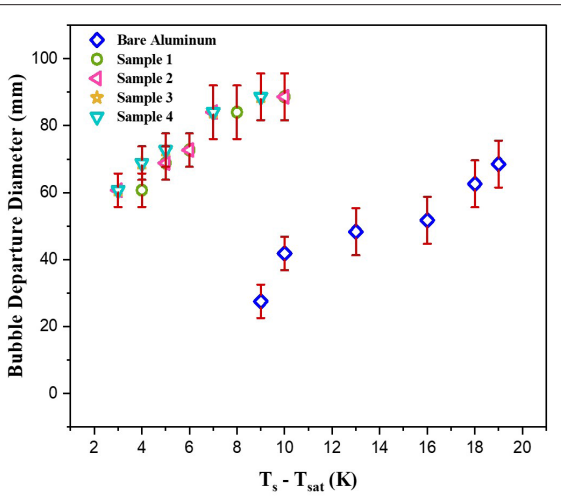


Figure 10: Bubble departure frequency variation with wall superheat.

Conclusions

In this present research work, aluminum-based nanocomposite is made on bare aluminum surface using the dip coating technique. Surface characterization has been completed, surface properties like wettability and Ra are measured. Experimental analysis of pool boiling heat transfer of prepared surface and bare aluminum is performed by using DI water as working fluid. Bubble dynamics of the pool boiling heat transfer is also analyzed. Findings are summarized below:

- The dip coating process is used to fabricate the nanocomposite on bare aluminum surface using hybrid nanomaterial of AgNPs + GO. Four different samples are prepared using different concentrations of hybrid nanofluid. AgNPs and GO are used in a 2:1 ratio, for making nanofluids of different concentration.

- As concentration of hybrid nanofluid increases from 0.3% to 1.2% the wettability and Ra of the samples increases. sample 4 provides more wettability compared to the other modified surface. Ra value is also high 12.72 µm for sample 4 and lowest 5.66 µm for sample 1.
- Sample 4 exhibits highest CHF and BHTC value of 2549.6 kW/m^2 and 185.29 kW/m^{2}K, respectively, which is 145.76% for CHF and 259.08% for BHTC, more compared to the uncoated surface.
- The combination of AgNPs + GO leads to a remarkable boiling heat transfer performance compared to bare aluminum surface, which may be useful for cooling purposes.

Acknowledgements

None.

Conflict of Interest

None.

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