Research Article

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Experimental Study of Pool Boiling Characteristic of Al_2O_3-coated Aluminum Surfaces

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ABSTRACT

The current study investigates the pool boiling performance of bare Al and Al_2O_3 nano-coated heating surfaces using refrigerant R-600a. The sol-gel technique was used to prepare Al_2O_3 nano-coatings. Using scanning electron microscopy, the crystal structure of coated surfaces was examined, and element percentage distribution across the coated surfaces was studied using energy-dispersive spectroscopy technology. The prepared heating surfaces S-100 nm, S-200 nm, and S-300 nm showed a maximum increase in heat transfer coefficient of around 29%, 36%, and 46%, respectively, as compared to plain Al heating surface. The improvement in heat transfer coefficient observed on Al_2O_3 nano-coated surfaces is primarily attributed to the presence of a high density of nucleation sites and increased surface roughness. This study will become increasingly important in the upcoming years due to the advancement of surface modification in energy conversion regulation and thermal applications.

Keyword: Pool boiling; HTC; Sol-gel; BHT; Heat transfer.

1. INTRODUCTION

Pool boiling is a highly efficient mode of heat transfer that occurs when a heated surface in contact with a saturated liquid initiates the formation of vapour bubbles. These bubbles grow, coalesce, and detach from the surface, carrying away significant thermal energy. The efficiency of this process, especially in the nucleate boiling regime, makes it vital for numerous engineering systems that demand rapid and effective thermal management. Applications span across a wide array of sectors, including energy generation, microelectronics cooling, refrigeration, aerospace, and chemical processing. As electronic devices become increasingly compact and high-powered, the demand for advanced thermal management technologies capable of dissipating high heat fluxes continues to escalate (Pingale *et al*. 2020). Phase change heat transfer, particularly nucleate boiling, has received considerable attention due to its capacity to transfer large quantities of heat with minimal temperature difference. This is primarily attributed to the high latent heat involved in the phase transition from liquid to vapour. Within the nucleate boiling regime, two key performance parameters are typically considered: the boiling heat transfer coefficient (BHTC), which reflects the efficiency of heat exchange, and the critical heat flux (CHF), which marks the upper limit of heat transfer before film boiling initiates (Park *et al*. 2010; Cooke *et al*. 2011; Das *et al*. 2014). Achieving high BHTC and delaying CHF are primary goals in designing high-performance boiling surfaces (Gupta *et al*. 2020; Katarkar *et al*. 2022).

One of the emerging solutions to meet these goals is the use of environmentally friendly refrigerants. Among these, refrigerant R-600a (isobutane) has garnered attention due to its low global warming potential (GWP), high energy efficiency, and ability to operate under moderate pressure. These properties not only make R-600a a suitable alternative to conventional hydrofluorocarbon (HFC)-based refrigerants but also enable more compact and cost-effective cooling systems. Furthermore, R-600a's compatibility with existing refrigeration infrastructure reduces the need for extensive retrofitting, enhancing its practical applicability. As sustainability becomes a growing concern in thermal systems, the transition to low-GWP refrigerants such as R-600a aligns well with global environmental goals and regulatory trends. Apart from working fluid selection, surface characteristics play a critical role in dictating boiling behaviour. The structure, roughness, porosity, and wettability of the heating surface profoundly influence bubble nucleation, growth, detachment, and departure frequency. Numerous studies have confirmed that enhancing the surface area and increasing nucleation site density can significantly improve heat transfer during pool boiling. As a result, research has shifted toward developing advanced surface coatings that passively

enhance boiling heat transfer without altering system configuration.

To this end, a variety of surface modification techniques—such as vibrational stimulation, fluid additives, and surface texturing—have been explored (Kim *et al*. 2015; Gupta *et al*. 2018; 2019). Among these, the application of micro- and nano-engineered coatings has proven to be one of the most promising approaches. These coatings create hierarchical structures that increase nucleation site density, modify liquid spreading behaviour, and improve bubble detachment, all of which contribute to enhanced boiling performance (Liu *et al*. 2016; Satpathy *et al*. 2021). Notably, surface coatings also offer the advantage of being adaptable to existing heat transfer equipment, thereby facilitating easier integration into industrial systems. Numerous fabrication methods have been developed to produce such coatings, including physical vapour deposition, dip coating, chemical vapour deposition, e-beam evaporation, electrodeposition, RF sputtering, and spray coating (Karunagaran *et al*. 2003; Ujereh *et al*. 2007; Ahmad *et al*. 2014; Patil *et al*. 2014). Among these, the dip coating technique, especially when combined with sol-gel chemistry, has emerged as a preferred approach owing to its simplicity, low equipment cost, scalability, and ability to achieve uniform and controllable coating thicknesses (Pialago *et al*. 2013; Ali *et al*. 2017). These characteristics make dip coating particularly attractive for fabricating aluminium oxide (Al_2O_3)-based coatings, which have shown significant potential in enhancing pool boiling performance.

Al_2O_3 coatings improve thermal performance primarily by increasing surface wettability and altering surface topography, which leads to more active and stable bubble dynamics. The material's excellent thermal and chemical stability ensures long-term durability, making it ideal for high-demand, high-temperature applications. Furthermore, Al_2O_3 coatings resist degradation in harsh working environments, reducing maintenance requirements and improving system longevity. These advantages position Al_2O_3 as a strategic material in both traditional and emerging boiling-based thermal systems, including those used in waste heat recovery, renewable energy, and biomedical temperature regulation. Despite extensive research in this area, limited studies have systematically investigated the effect of coating thickness on pool boiling performance, particularly using low-GWP refrigerants like R-600a. Understanding the relationship between surface thickness and parameters such as BHTC and CHF can reveal valuable insights into optimizing surface designs for practical implementation. Further, the surface properties must be comprehensively analyzed to establish correlations between coating structure and boiling performance.

In this study, Al_2O_3 nanoparticle coatings with varying thicknesses—100 nm, 200 nm, and 300 nm—were fabricated on bare aluminium substrates using the sol-gel dip coating technique. The primary objective is to evaluate the influence of coating thickness on BHT performance using refrigerant R-600a. Comprehensive surface characterization was performed using techniques such as scanning electron microscopy attached with energy dispersive spectroscopy (SEM-EDS) and surface roughness analyzer to assess surface morphology, roughness, and porosity. The pool BHT performance of each coated surface was experimentally measured and analyzed in terms of HTC. The findings of this study add to the existing knowledge on passive methods for enhancing boiling heat transfer and provide useful insights for designing efficient and environmentally sustainable thermal management systems. This work particularly holds relevance for Indian industries and research institutions focusing on energy-efficient cooling solutions in sectors such as power electronics, refrigeration, automotive, and process engineering. Moreover, the use of a low-cost and scalable sol-gel dip coating technique demonstrates a practical approach to improve heat transfer performance, making it suitable for deployment in both academic research and industrial applications across the country. The outcomes of this work support the development of indigenous technologies in line with the growing need for reliable and compact cooling systems in India's rapidly advancing electronics and thermal sectors.

2. EXPERIMENTAL SETUP

Figure 1 presents the schematic layout of the experimental setup used for pool boiling investigations. The apparatus comprises a boiling chamber, test specimens, an aluminum heating block, a DC power supply, a condensation system, and thermal insulation components. At the heart of the setup is a cylindrical boiling chamber constructed from stainless steel (SS-316), measuring 314.5 mm in height and 115 mm in internal diameter. To allow visual observation of the boiling process, the chamber is fitted with two circular Pyrex glass windows mounted on polycarbonate boards. Positioned at the top of the chamber are essential components for refrigerant handling, including a refrigerant charging unit, a pressure gauge, and an on/off pressure switch. The pressure gauge monitors the internal chamber pressure during operation. To maintain a consistent temperature inside the chamber, it is equipped with a condenser coil connected to a chiller unit. Additionally, an auxiliary heater is employed to keep the liquid refrigerant (R-600a) at its saturation temperature. To minimize heat loss, glass wool insulation is applied to all connecting pipelines and the boiling chamber itself. The heating system comprises an aluminum heating block, the test surface, thermal insulation, thermocouples, and a heater. The flat, circular test surface is placed directly atop the aluminum heating block, which houses a 0.5 kW cartridge heater at its core to supply heat. A Teflon bush is positioned between the

test surface and the lower flange of the boiling chamber to minimize thermal resistance and reduce heat loss. Electrical power to the heater is controlled using a variac, while voltage and current are monitored via a voltmeter and an ammeter, respectively. For accurate temperature measurement and heat flow analysis, three K-type thermocouples are embedded circumferentially at 120° intervals within the aluminum block.

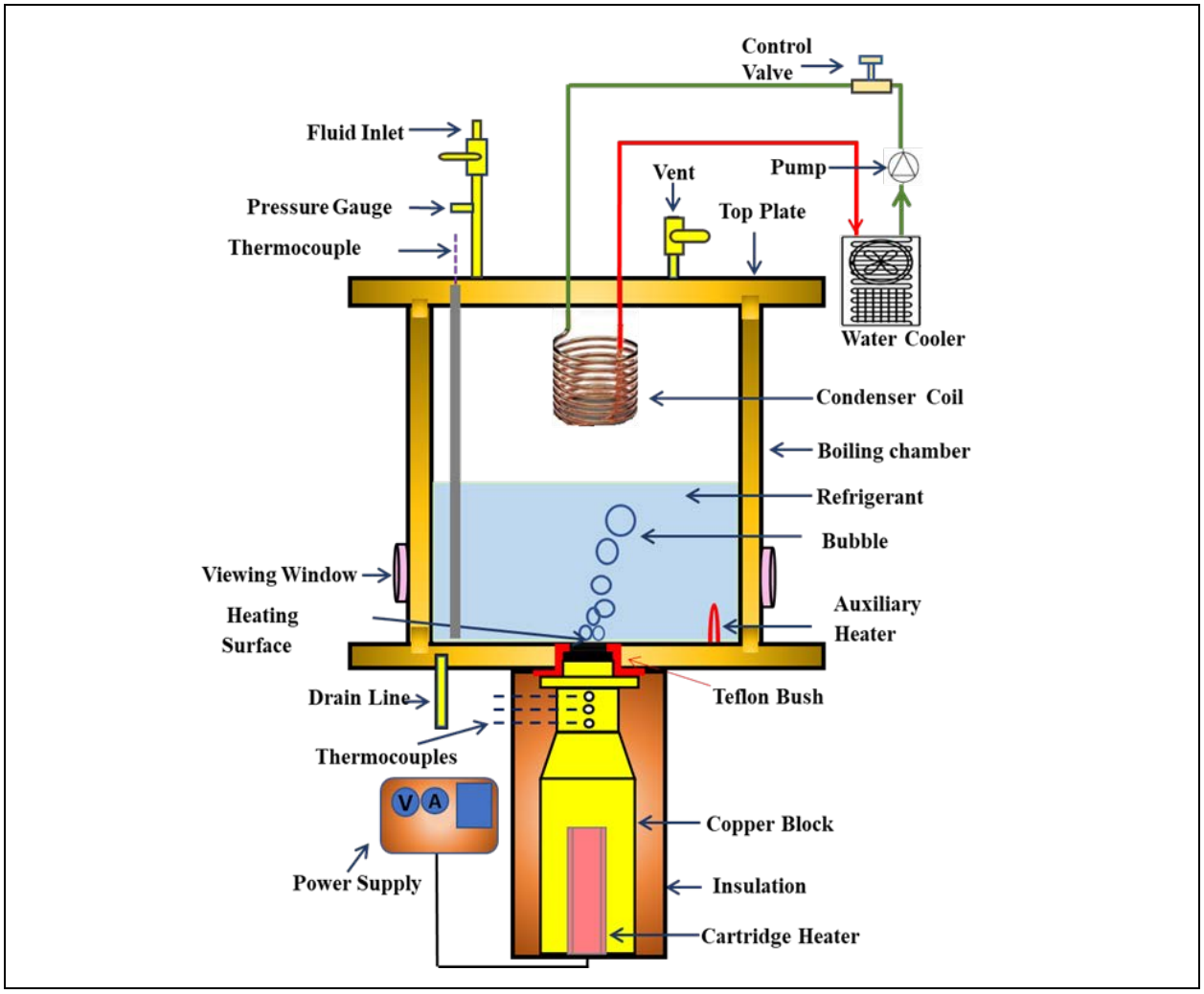


Fig. 1: Schematic of the experimental arrangement of pool boiling

3. EXPERIMENTAL PROCEDURE

Experiments were performed on both uncoated and Al_2O_3 nano-coated aluminum samples using R-600a. Before each test run, the boiling chamber was thoroughly cleaned with acetone to eliminate any contaminants. An aluminum heating block was positioned at the bottom of the boiling chamber to act as the source of heat. Upon completing all fittings, nitrogen gas was introduced into the chamber as a leak detection measure. Then, a vacuum pump was employed to evacuate the chamber and prepare it for refrigerant charging. To remove dissolved non-condensable gases, the refrigerant was preheated for two hours using an auxiliary heater. Heat flux measurements were conducted in incremental steps, ranging from 9.17 kW/m² to 72.27 kW/m². At each step, the temperature was maintained at a constant saturation level to ensure steady-state conditions. Heat flux was determined from electrical power input by measuring voltage and current supplied to the cartridge heater. To validate repeatability, three additional tests were conducted for each sample, and one replicate experiment was performed 24 hours later under identical conditions.

4. SURFACE PREPARATION

The sol-gel dip coating technique is a widely employed method for depositing thin, uniform coatings onto substrates, and in this study, it was effectively utilized to apply an Al_2O_3 (aluminium oxide) nano-coating onto aluminium (Al) test surfaces using an Al_2O_3 sol-gel solution. This process, as illustrated in Figure 2, involves a series of well-defined steps—dipping, withdrawal, and evaporation—that collectively ensure the formation of a high-quality nano-coating. The specific parameters used during the dipping process—

such as lift and dip speed, wet time, dry time, and number of cycles—are detailed in Table 1. To achieve uniform and well-controlled coating thicknesses, key parameters in the dip-coating process were carefully varied and optimized. At the heart of this process is the preparation of a stable and homogeneous Al_2O_3 sol-gel solution. High-purity Al_2O_3 nanoparticles (99% purity, with an average particle size between 20 and 50 nm) were selected as the coating material. Dimethylformamide (DMF) was used as the solvent due to its excellent ability to disperse nanoparticles effectively. The preparation began by dispersing 5 mg of Al_2O_3 nanoparticles into DMF. This mixture was magnetically stirred at 250 rpm for 3 hours to achieve initial homogeneity. To further refine the dispersion and eliminate nanoparticle agglomerates, the solution was then subjected to ultrasonication—a crucial step that ensures a stable sol-gel, which is essential for producing uniform and high-quality coatings during the dip-coating process. Before applying the Al_2O_3 nano-coating, the aluminium heating surface underwent a well-defined pre-treatment protocol to enhance coating adhesion, surface cleanliness, and uniformity of deposition. The surface was mechanically polished using progressively finer sandpapers (1000#, 1500#, and 2000#), which helped smooth out imperfections and refine the surface texture. This polishing step is vital for removing oxide layers and contaminants that could otherwise hinder proper coating adherence. After polishing, the aluminum surface was rinsed with acetone to eliminate any remaining debris or organic residues. Finally, the cleaned aluminium substrates were dried under vacuum conditions to eliminate any residual moisture. This step was necessary to avoid the formation of voids or irregularities in the coating, which could affect its uniformity and quality.

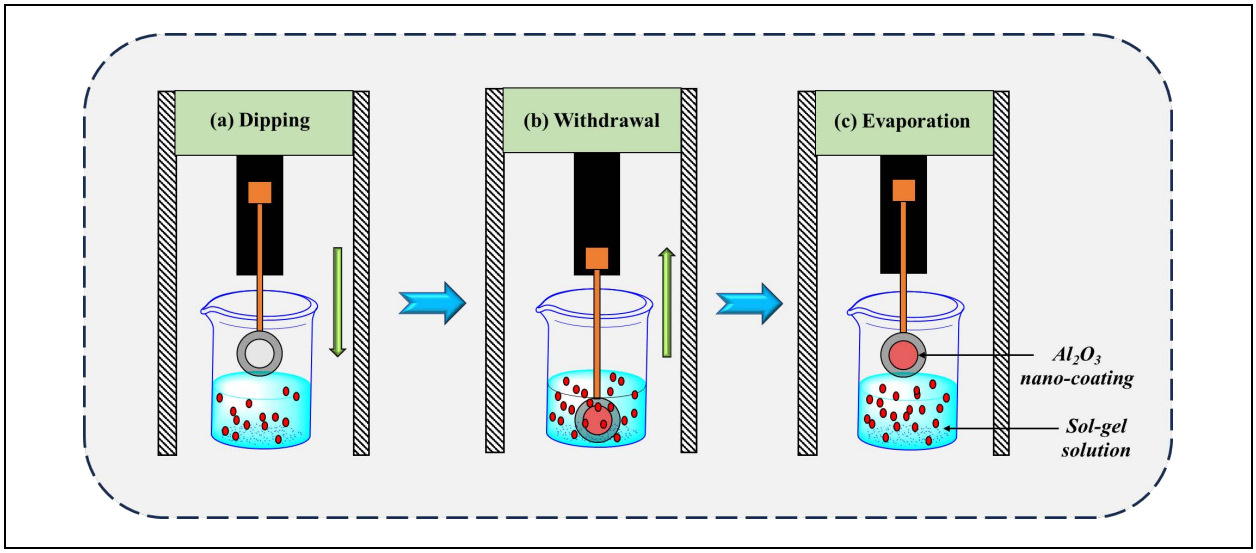


Fig. 2: Fabrication of Al_2O_3 nano-coatings using sol-gel dip coating technique

As illustrated in Figure 2, the dip-coating process comprises three main stages:

- Dipping (Fig. 2a): The prepared Al substrate, attached to a controlled lifting mechanism, is immersed into the Al_2O_3 sol-gel solution. This step allows the solution to thoroughly wet the surface, with the Al_2O_3 nanoparticles in the sol-gel adhering to the substrate. The duration of immersion and the properties of the sol-gel solution (e.g., viscosity and nanoparticle concentration) play a significant role in determining the initial coating thickness.

- Withdrawal (Fig. 2b): The substrate is slowly lifted from the sol-gel solution at a controlled speed. This stage is crucial for controlling the thickness of the coating, as the rate of withdrawal influences the amount of sol-gel solution that remains on the surface. The upward movement, as shown by the arrow in Figure 2b, allows excess solution to drain off, leaving a thin, uniform layer of Al_2O_3 nanoparticles adhered to the Al surface. Variations in lift speed, as detailed in Table 1, were explored to optimize the coating properties.

- Evaporation (Fig. 2c): After withdrawal, the solvent (DMF) begins to evaporate from the deposited layer, leaving behind a solid Al_2O_3 nano-coating. This stage is facilitated by ambient conditions or, in some cases, controlled heating. As illustrated in Figure 2c, the evaporation process results in the formation of a dense Al_2O_3 nano-coating on the Al surface, with the nanoparticles consolidating into a continuous film.

The final step involved heating the coated samples in a muffle furnace at 450°C for 60 minutes to enhance the adhesion and structural integrity of the coating by removing residual solvent and promoting particle bonding.

Table 1. Sol-gel dip coating technique operating conditions

Sample	Lift and dip speed (mm/min)	Wet time (min)	Dry time (min)	Number of cycles	Thickness (nm)
S-100 nm	250	30	60	9	100 ± 13
S-200 nm	300	30	60	10	200 ± 12
S-300 nm	350	30	60	11	300 ± 15

5. SURFACE CHARACTERIZATION

The morphology and composition of Al_2O_3 nano-coated heating surfaces were characterized using SEM equipped with EDS. Fig. 3(a) shows the surface morphology of the bare Al heating surface. The uncoated Al exhibits parallel grooves from the mechanical polishing process, with a relatively smooth and featureless surface. Fig. 3(b-d) shows the surface morphology of Al_2O_3 nano-coatings. According to Fig. 3(b-d), in surfaces coated with Al_2O_3 nanoparticles, fractal structures are discovered with increasing surface roughness. Considering SEM images as a basis, it is evident that roughness increases with the increase in coating thickness. Fig. 4 shows the EDS spectrum of the S-300 nm. In the EDS spectrum, Al and O spikes are observed, confirming the formation of Al_2O_3 nano-coating on the Al surface without contamination from other elements. Using a 2D profilometer, the surface roughness of Al_2O_3 nano-coated surfaces was measured. Fig. 5 displays the surface roughness of S-300 nm. It has been found that the nanostructure grows consistently at various thicknesses and that surface roughness is correlated with coating thickness.

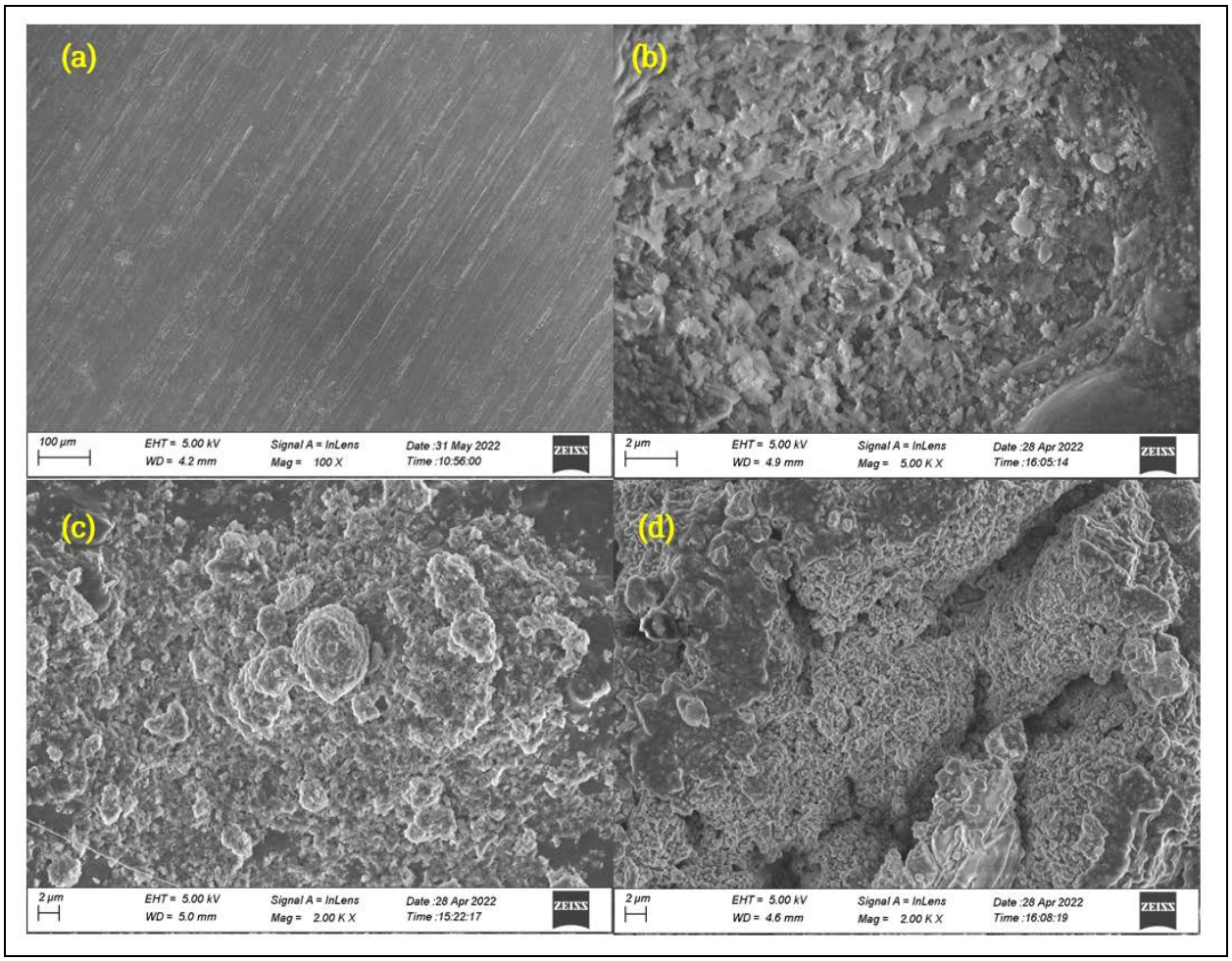


Fig. 3: SEM micrographs of (a) plain Al, (b) S-100 nm, (c) S-200 nm, and (d) S-300 nm

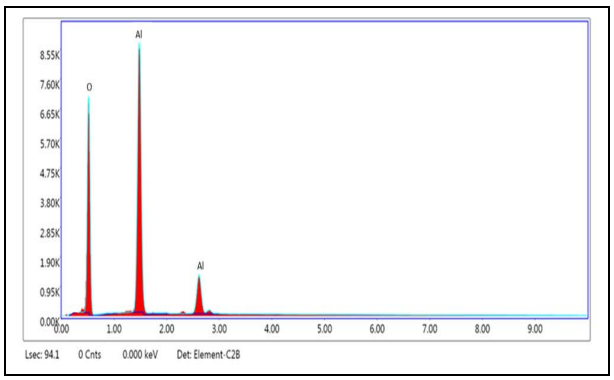


Fig. 4: EDS spectrum of S-300 nm

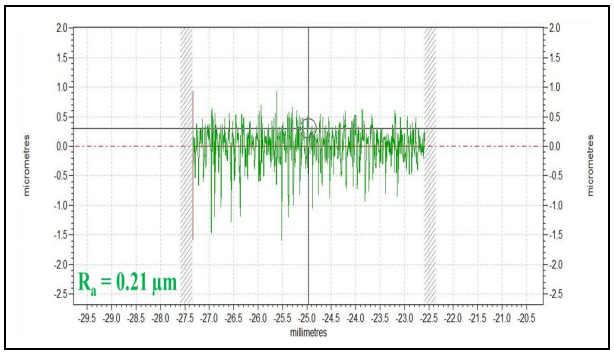


Fig. 5: Surface roughness profile of S-300 nm

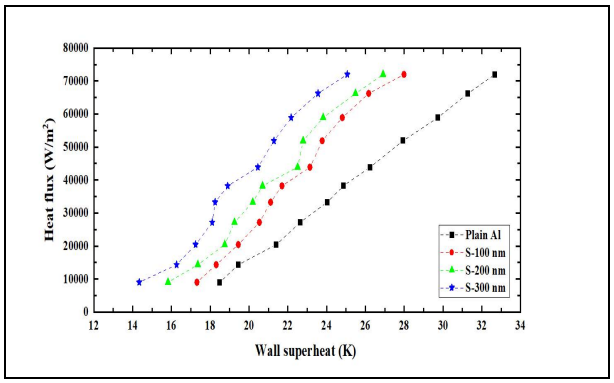


Fig. 6: Variation of wall superheat with heat flux

6. RESULT AND DISCUSSION

Fig. 6 presents the relationship between wall superheat (ΔT) and heat flux (q) for plain aluminum (Al) and Al_2O_3 nano-coated heating surfaces prepared with varying thicknesses (100 nm, 200 nm, and 300 nm). The results indicate that the Al_2O_3 nano-coated surfaces significantly outperform the plain Al surface in terms of heat transfer efficiency. This enhancement is attributed to the high density of active nucleation sites formed by the microporous structure of the Al_2O_3 layer, which promotes efficient liquid-vapour phase change. Additionally, the nano-coating enhances capillary wicking, aiding liquid replenishment to the heated surface. The three-step dipping process used to create these coatings results in increased surface roughness and improved walkability, fostering efficient bubble nucleation and detachment. At low wall superheats, the increase in heat transfer is predominantly due to the initiation of numerous nucleation sites, while at higher heat flux levels, the improvement is governed by intensified micro-convection caused by rapid bubble generation and smaller bubble departure sizes. Collectively, these effects confirm that Al_2O_3 nano-coatings offer a significant advantage for pool BHT applications.

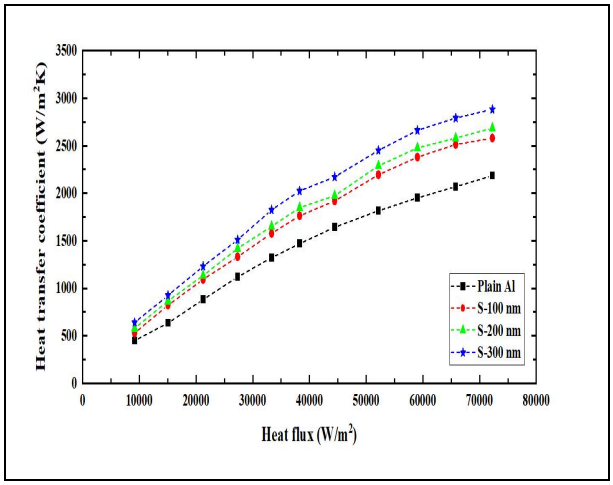


Fig. 7: Relationship between HTC vs. heat flux for plain Al and Al_2O_3 nano-coated heating surfaces

Fig. 7 illustrates the variation of the heat transfer coefficient (h) concerning heat flux (q) for both plain aluminum and Al_2O_3 nano-coated surfaces with varying coating. The results demonstrate that all nano-coated surfaces exhibit superior heat transfer performance compared to plain Al, with the 300 nm coating showing the most pronounced enhancement. As the heat flux increases to 72,270 W/m², the plain Al surface reaches around 2185 W/m²K, while the 300 nm Al_2O_3-coated surface exceeds 2883 W/m²K—indicating an approximate 32% improvement. This improvement is primarily attributed to the porous and micro-structured morphology of the Al_2O_3 coatings, which significantly increases the density of active nucleation sites. As the refrigerant contacts the coated surface, the microcavities and pores become wetted, facilitating early bubble nucleation. The porous structure traps vapour pockets and supports continuous rewetting of the surface, promoting efficient phase change heat transfer. Among the tested samples, the 300 nm Al_2O_3 coating yields the highest heat transfer coefficient at all heat flux levels. This is due to the greater surface roughness and enhanced microporosity at higher coating thickness, which accelerates bubble formation and departure frequency. As a result, for any given heat flux, the wall superheat required is significantly lower compared to the plain Al surface. Overall, the data confirms that the nano-coated surfaces effectively reduce thermal resistance at the liquid-solid interface, leading to enhanced heat flux at lower superheat values. This makes Al_2O_3 nano-coatings

a promising approach for improving thermal performance in boiling or high-flux heat transfer applications.

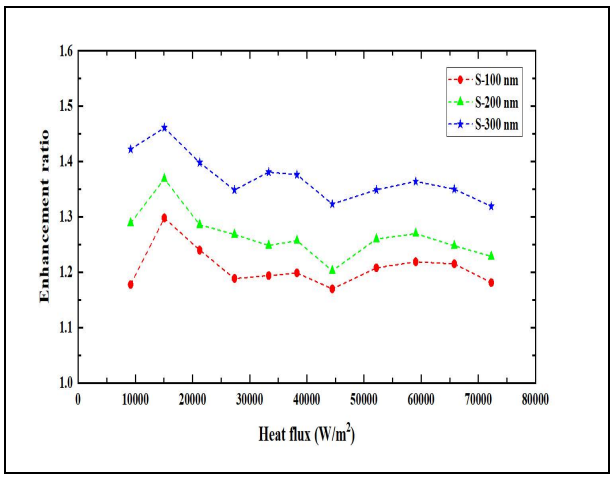


Fig. 8: Enhancement ratio versus heat flux

Figure 8 shows the variation of enhancement ratio as a function of heat flux for aluminum surfaces coated with Al_2O_3 at three different thicknesses. The enhancement ratio—defined as the ratio of the boiling heat transfer coefficient (HTC) of a coated surface to that of an uncoated one—is a valuable measure for assessing how effective a surface modification is. In this study, all three Al_2O_3-coated surfaces demonstrated enhancement ratios greater than one across the full range of heat fluxes, clearly indicating improved boiling performance due to the coatings. Among the samples tested, the S-300 nm coating stood out, consistently showing the highest enhancement ratio, reaching up to about 1.46. This improvement is primarily credited to the increased surface roughness, higher porosity, and better wettability that come with thicker coatings. These features help create more active nucleation sites and support efficient bubble formation and release. The S-200 nm coating also performed well, with enhancement ratios peaking around 1.36, while the S-100 nm coating showed the least improvement, with values around 1.29. Overall, the results suggest that thicker coatings have a more significant impact on enhancing heat transfer. This effect is especially noticeable at lower heat fluxes (below 20,000 W/m²), where the surface properties play a more dominant role in the nucleate boiling process. As the heat flux increases, the enhancement ratio stabilizes, particularly for the S-300 nm surface, suggesting that the coating maintains effective performance even under higher thermal loads. This stability at elevated heat fluxes indicates that the thicker coating not only enhances initial nucleation but also supports sustained boiling activity.

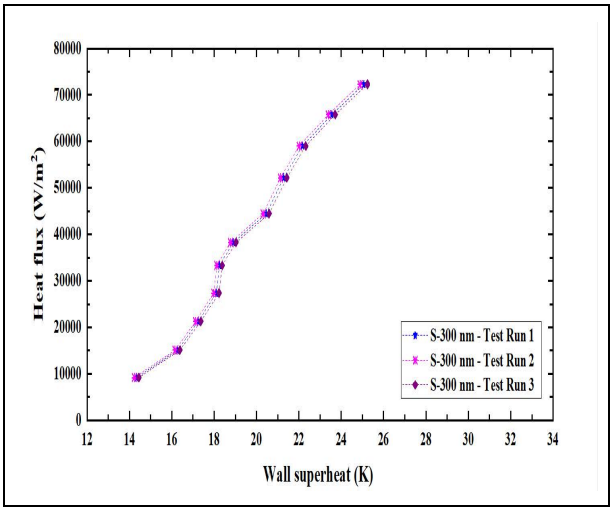


Fig. 9: Reproducibility of Al_2O_3 coated Al surface

Table 2. HTC comparison of present study with previously reported coatings in pool boiling.

Coating Technique	Base Surface	Working Fluid	Coating	Improvement Compared to Bare Surface	Ref.
Sol-gel dip coating	Aluminum	R-600a	Al_2O_3	HTC increased by 46%	Present work
Dip coating	Cu	DI water	GO	HTC increased by 47%	(Jaikumar *et al*. 2017)
Sol-gel dip	Stainless-steel	DI water	CuO	HTC increased by 30%	(Joseph *et al*. 2019)
CVD	Si	PF-5060	MWCNT	HTC increased by 28%	(Ahn *et al*. 2006)
Electron beam evaporation	Cu	R-134a	TiO_2	HTC increased by 44.93%	(Ray *et al*. 2017)

The Al_2O_3-coated aluminum surface, with a coating thickness of 300 nm, was subjected to reproducibility tests to guarantee the accuracy and consistency of the experimental data. Under the same operational conditions, three separate test runs were carried out. Figure 9 shows the results of each run, which measured the boiling heat transfer performance in terms of heat flux as a function of wall superheat. Plotting the data reveals essentially matching trends over the range of wall superheats, indicating good agreement across all three test runs. The reproducibility of the boiling heat transfer properties on the Al_2O_3-coated surface is confirmed by this extraordinary degree of uniformity. The slight differences between the runs can

be ascribed to the coating's microstructural changes brought on by extended boiling exposure. However, the overall heat transfer behaviour was barely affected by these modifications, which strengthened the Al_2O_3 coating's mechanical and thermal stability. The study's reproducibility demonstrates the surface modification technique's dependability and bolsters the potential of Al_2O_3 coatings for reliable and long-lasting thermal performance in boiling heat transfer applications.

Table 2 compares the HTC enhancement of the Al_2O_3-coated aluminum surfaces with previously reported heating surfaces. The results show that the prepared Al_2O_3 coatings offer similar or better performance, demonstrating their suitability for practical, cost-effective thermal applications in Indian settings.

7. CONCLUSION

In this study, Al_2O_3 nano-coatings were successfully applied to plain aluminum heating surfaces using a controlled dip-coating technique. Multiple coatings with varying thicknesses were produced by adjusting the number of dipping cycles. Pool boiling experiments were conducted using R-600a as the working fluid at saturation conditions, with heat flux values ranging from 9.17 kW/m² to 72.27 kW/m². Surface morphology analysis via SEM revealed the formation of microporous structures on the coated surfaces, while EDS confirmed the presence of Al and O, verifying the successful deposition of Al_2O_3. Boiling performance was assessed through the development of boiling curves at different coating thicknesses. Results showed a clear enhancement in the heat transfer coefficient with increasing coating thickness, attributed to the improved nucleation site density. Among all samples, the Al_2O_3 nano-coated surface with a 300 nm thickness (S-300 nm) achieved the highest performance, recording an enhancement ratio of 1.46. These findings suggest that Al_2O_3 nano-coatings offer significant potential for enhancing pool boiling heat transfer and can be effectively employed in advanced thermal management systems.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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