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A REVIEW ON NUCLEATE POOL BOILING HEAT TRANSFER ENHANCEMENT USING NANOSTRUCTURED AND CARBON-BASED COATED SURFACES

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Abstract : Nucleate pool boiling heat transfer (NPBHT) has gained significant research interest due to its ability to transfer high heat fluxes with minimal temperature differences, making it vital in power generation, refrigeration, and thermal management applications. The enhancement of critical heat flux (CHF) and boiling heat transfer coefficient (HTC) has become a focal area of study, especially through surface modification using nanostructured and carbon-based coatings. This paper presents a comprehensive review of experimental and theoretical investigations on NPBHT conducted over the past two decades. It covers enhancement mechanisms, surface modification methods, coating materials, and the influence of substrate and working fluid characteristics. Particular attention is given to carbon-based materials such as graphene and carbon nanotubes (CNTs) due to their exceptional thermal conductivity. The review identifies existing research gaps in using graphene–aluminium composites and aluminium-coated aluminium surfaces with low global warming potential (GWP) refrigerants such as R-134a and R-600a. The paper concludes by suggesting the need for further experimental validation of such coated surfaces to develop sustainable and high-efficiency heat transfer systems.

Keywords
Nucleate Pool Boiling; Heat Transfer Enhancement; Nanostructured Surface; Carbon Nanotubes; Graphene; Aluminium Coating; Critical Heat Flux; Refrigerants

1. Introduction

Heat transfer through boiling is one of the most efficient modes of thermal energy transport, commonly employed in heat exchangers, power plants, refrigeration systems, and electronic cooling. Nucleate pool boiling (NPB) occurs when a heated surface submerged in a stagnant liquid produces vapor bubbles at localized nucleation sites [1]. Its efficiency arises from phase change heat transfer and the high latent heat of vaporization. The effectiveness of this process depends on surface morphology, fluid properties, and operating conditions.

Conventional heat exchangers face limitations due to the critical heat flux (CHF) phenomenon, where excessive surface temperature leads to a vapor blanket formation, drastically reducing heat transfer [2]. Therefore, improving CHF and boiling heat transfer coefficient (HTC) through surface engineering has been a primary focus of researchers [3], [4]. Enhanced and coated surfaces—particularly with nano-structured and carbon-based materials—have demonstrated remarkable improvements in heat transfer performance.

2. Methodology of Literature Review

This review is based on an extensive examination of over 100 scholarly articles, focusing on experimental and analytical studies between 1990 and 2024. Sources include peer-reviewed journals such as *International Journal of Heat and Mass Transfer*, *Applied Thermal Engineering*, and *Experimental Heat Transfer*. The papers were grouped under themes such as enhancement techniques, nanocoating materials, refrigerants, and substrate influence. Only the most relevant 40–50 studies were included to synthesize a concise yet comprehensive review.

3. Fundamentals of Nucleate Pool Boiling Heat Transfer

In nucleate boiling, bubbles form at active nucleation sites when the wall superheat—defined as the temperature difference between the wall and fluid saturation temperature—reaches a threshold [5]. The boiling process can be divided into regimes: natural convection, onset of nucleate boiling (ONB), fully developed nucleate boiling, and film boiling [6].

The classical boiling curve proposed by Nukiyama (1934) demonstrates that heat flux increases with wall superheat until reaching CHF, beyond which film boiling dominates. Enhancing nucleate boiling requires shifting the curve leftward (earlier boiling onset) and upward (higher CHF) [7]. Key influencing factors include surface roughness, wettability, microcavity density, and capillary wicking effects.

4. Enhancement Techniques in Pool Boiling

Enhancement methods are broadly classified into **passive**, **active**, and **compound** techniques [8].

- **Passive methods** involve surface modification, roughening, extended surfaces, or coatings without external power input [9].
- **Active methods** require external energy, such as magnetic fields or surface vibrations [10].
- **Compound methods** combine both.

Among these, passive techniques are most popular due to simplicity and reliability. Techniques like sintering, sandblasting, laser texturing, electrodeposition, and nanoparticle coating significantly alter surface properties, enhancing bubble dynamics and capillary effects [11]–[13].

Katarkar et al. [14] and Meena et al. [15] reviewed passive techniques and noted that micro/nano coatings on flat surfaces can enhance CHF by up to 300%. Twisted tapes, wire coils, and microfins further augment turbulence and heat transport in pool boiling systems [16]–[18].

5. Pool Boiling on Enhanced and Nanostructured Surfaces

Surface roughness and micro/nano-structuring have a significant influence on boiling performance. Studies confirm that modifying surfaces via sintering, spraying, or electrodeposition can drastically improve CHF and HTC [19]–[21]. Materials like copper, stainless steel, and aluminum are common substrates.

Nanofluids—suspensions of nanoparticles in base fluids—were first explored by You et al. [22], who reported a 200% CHF increase with alumina–water nanofluids. Subsequent work by Kim et al. [23] and Liu et al. [24] showed that nanoparticle deposition during boiling forms porous coatings, enhancing wettability and nucleation density.

Recent experiments indicate that porous surfaces, re-entrant microchannels, and hybrid micro-nano coatings enhance CHF by 2–5 times compared with smooth surfaces [25]–[28]. Hwang and Kaviany [29] demonstrated that separated liquid and vapor flow paths via micro-porous coatings significantly improve boiling stability.

6. Carbon-Based Nanocoatings: CNTs and Graphene

Carbon nanotubes (CNTs) and graphene possess extraordinary thermal conductivities exceeding 3000 W/mK, making them promising candidates for thermal applications [30], [31].

CNT-coated surfaces increase active nucleation site density and delay CHF occurrence. Dharmendra et al. [32] reported a 38.5% CHF enhancement on CNT-coated copper substrates using deionized water. Seo et al. [33] observed 55% HTC and 18% CHF improvements with GNP/SWCNT composite coatings.

Hybrid coatings combining CNTs with metallic substrates further boost performance. Ahn et al. [34] achieved 25–28% CHF increase using multi-walled CNT coatings via CVD. Jaikumar et al. [35] reported a 47% HTC improvement for graphene oxide (GO)-coated copper surfaces. Kumar et al. [36] combined CNT and graphene using plasma-enhanced CVD, achieving 155% HTC and 40% CHF enhancement.

These findings highlight that carbon-based coatings improve both thermal conductivity and wettability, though challenges remain in adhesion strength and cost-effective synthesis.

7. Role of Substrate and Refrigerant

Substrate material strongly affects boiling characteristics. Ideal substrates have high thermal conductivity, chemical stability, and good wettability. Copper and aluminum are most widely used; aluminum is preferred for its low weight, cost, and corrosion resistance [37]. Studies show that anodized or nano-porous aluminum surfaces exhibit up to 100% higher CHF compared to bare aluminum [38]–[40].

Refrigerants as working fluids determine bubble behavior and nucleation dynamics. Refrigerants like R-134a and R-600a have been studied extensively for their environmental compatibility and thermophysical properties [41]. Experiments confirm that surface modification combined with suitable refrigerants can yield CHF enhancement up to fourfold [42]–[45].

With the global phase-down of high-GWP refrigerants under the Kigali Amendment, R-600a (isobutane) emerges as a sustainable alternative with excellent heat transfer potential [46], [47].

8. Discussion and Research Gaps

From the literature, it is evident that nucleate pool boiling efficiency depends on synergistic effects between surface structure, coating materials, and working fluid properties. However, key gaps remain:

- Limited studies on **aluminium–graphene composite coatings** in refrigerant-based boiling systems.
- Few investigations using **low-GWP refrigerants (R-600a)** on **carbon-coated aluminium surfaces**.
- Insufficient long-term studies on coating durability, corrosion resistance, and performance degradation.
- Need for standardized testing methods to compare nanostructured surface results across different laboratories.

Future research should integrate material science and thermofluidic modeling to optimize coating–substrate–refrigerant interactions for sustainable heat transfer systems.

9. Conclusion

This review consolidates progress in nucleate pool boiling heat transfer with emphasis on nanostructured and carbon-based coatings. Enhancements in CHF and HTC achieved through CNTs, graphene, and nanostructured metal coatings have revolutionized pool boiling performance. Aluminum-based substrates, owing to their lightweight and cost-effectiveness, offer new opportunities when combined with graphene coatings.

The development of efficient, durable, and environmentally compatible surfaces—tested with low-GWP refrigerants like R-134a and R-600a—will play a pivotal role in next-generation thermal management systems. The identified research gaps pave the way for experimental and computational exploration of hybrid nano–micro surface architectures.

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