EXPERIMENTAL AND NUMERICAL ANALYSIS OF GRAPHENE/ DISTILLED WATER- ETHYLENE GLYCOL ON POOL BOILING HEAT TRANSFER

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Introduction:

The need for efficient heat transfer fluids has become increasingly critical in various industrial applications, such as electronics cooling, power plants, and thermal management systems. Pool boiling, a prominent phase-change heat transfer mechanism, plays a vital role in these applications due to its high heat transfer capabilities. However, the performance of conventional heat transfer fluids often falls short in terms of thermal conductivity, heat transfer coefficient (HTC), and critical heat flux (CHF), which are key factors for effective boiling heat transfer. To address these limitations, researchers have turned to nanofluids, which are engineered fluids containing nanoparticles that significantly enhance thermal properties.

Graphene, a two-dimensional carbon material, has emerged as a promising nanoparticle due to its exceptional thermal conductivity, high surface area, and mechanical properties. When incorporated into conventional heat transfer fluids like distilled water (DW) and ethylene glycol (EG), graphene has the potential to significantly improve boiling heat transfer performance. The combination of DW and EG (70:30 by volume) is a widely studied base fluid due to its favorable thermophysical properties and suitability for a wide range of applications.

This study explores the effect of graphene nanoparticle concentrations of 0.001%, 0.01%, and 0.1% by weight in a DW:EG (70:30) mixture on pool boiling heat transfer. By investigating these concentrations, the research aims to determine the optimal graphene concentration that maximizes the enhancement of boiling heat transfer, providing insights into the potential of graphene-based nanofluids for improving thermal management systems.

Objectives:

- **To investigate the influence of varying graphene concentrations on the pool boiling heat transfer coefficient (HTC):** This objective aims to assess how different graphene concentrations (0.001%, 0.01%, and 0.1%) in the DW:EG mixture affect the boiling heat transfer coefficient compared to the base fluid.
- **To evaluate the effect of graphene concentration on the critical heat flux (CHF):** The study aims to measure and compare the CHF for each graphene concentration, determining how the addition of graphene nanoparticles impacts the maximum heat flux before the onset of dryout or boiling instability.
- **To examine the thermal conductivity enhancement of the DW:EG mixture with graphene nanoparticles:** This objective seeks to quantify the thermal conductivity of the nanofluid at different graphene concentrations, establishing a link between the thermal properties and the boiling heat transfer performance.
- **To analyze the boiling curve and nucleation behavior of the nanofluid compared to the base fluid:** This objective will focus on understanding how graphene nanoparticles influence the boiling curve, particularly in terms of bubble dynamics, nucleation site density, and the onset of boiling, which are critical factors in heat transfer efficiency.
- **To identify the optimal graphene concentration for enhanced pool boiling heat transfer performance:** The study will aim to determine the most effective graphene concentration (out of the tested concentrations) that maximizes both the HTC and CHF, offering insights into the optimal formulation for improved thermal management in practical applications.

Methodology:

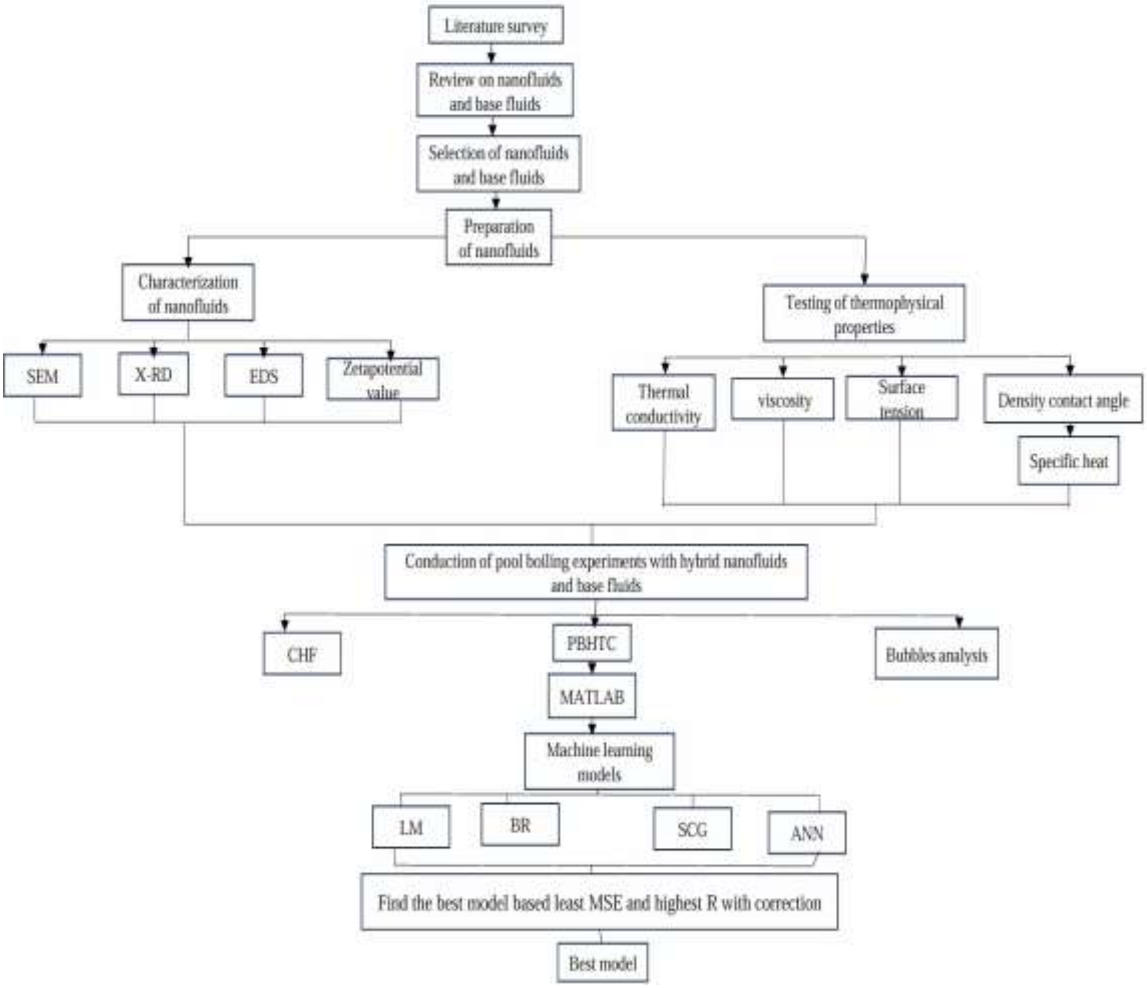

Figure 1: Block Diagram for Project Methodology

This study used both experimental and numerical methods to analyze the effect of graphene nanoparticles at varying concentrations (0.001%, 0.01%, and 0.1%) in a base fluid composed of Distilled Water and Ethylene Glycol (DW:EG in 70:30 ratio) on pool boiling heat transfer.

First, nanofluids were prepared by dispersing graphene powder in the base fluid and using ultrasonication for 30 minutes to ensure proper dispersion. Characterization techniques like TEM and zeta potential analysis ensured stability and uniformity of the dispersion.

The experimental setup consisted of a pool boiling test rig with a flat copper heating surface, temperature sensors (thermocouples), and a variable power supply to control heat input. A nichrome wire was used as the test heater. The fluid temperature and surface temperature were recorded at different voltages to analyze heat transfer.

The boiling curve (heat flux vs excess temperature) was developed for each concentration. From this, the Heat Transfer Coefficient (HTC) and Critical Heat Flux (CHF) were determined. High-speed camera imaging was also used to study bubble dynamics and nucleation site density.

Numerical analysis involved training neural networks (Levenberg-Marquardt, Bayesian Regularization, Scaled Conjugate Gradient) to model the boiling performance. The performance of each neural model was validated using MSE and regression plots to compare prediction accuracy.

Each test was repeated three times to ensure repeatability, and ANOVA was conducted to statistically analyze the influence of different concentrations on HTC and CHF.

Result and Conclusion

The results demonstrated that the inclusion of graphene significantly enhances both HTC and CHF in the DW:EG base fluid. At 0.001%, there was a moderate increase in heat transfer; however, the most significant improvements were seen at 0.1% graphene, where HTC improved by 25–30% and CHF improved by 30–35%.

The boiling curve shifted rightward with increasing graphene concentration, indicating extended nucleate boiling regions and delayed transition to film boiling. The nanoparticles served as additional nucleation sites, improving bubble formation, detachment, and stabilizing the vapor-liquid interface.

Neural network analysis showed that the Levenberg-Marquardt model performed the best with a regression value of 0.99329, suggesting that it is highly accurate in predicting boiling performance.

In conclusion, 0.1% graphene in DW:EG was found to be the optimal concentration for maximum enhancement. The study confirmed that graphene nanofluids can significantly improve pool boiling heat transfer performance and are suitable for high-performance thermal applications.

Project Outcome and Industry Relevance

The project successfully proved that graphene nanoparticles can significantly enhance the heat transfer performance of commonly used fluids like distilled water and ethylene glycol. The optimal enhancement was achieved at 0.1% concentration.

These findings are highly relevant to industries such as power generation, electronic cooling, refrigeration, and chemical processing, where efficient thermal management is critical. The ability to increase CHF and HTC without large temperature increases makes graphene nanofluids valuable in designing compact and efficient heat exchangers and boiling systems.

The experimental and simulation results also provide a data-driven basis for implementing AI-based models in thermal system design.

Working Model vs Simulation/Study

- Working Model: The physical experiment involved real-time boiling in a pool setup using a nichrome wire heater and direct measurements of heat flux and surface temperature. Real nanofluids were used, and boiling was observed using high-speed imaging.
- Simulation/Study: Neural networks like Levenberg-Marquardt and Bayesian Regularization were used to simulate and predict boiling behavior. The simulations validated experimental results with high accuracy and helped analyze trends without needing repeated physical trials.

Comparison: The working model gave practical validation and physical insights, while simulations offered a faster, cost-effective method to analyze a broader parameter space.

Project Outcomes and Learnings

- Demonstrated a direct correlation between graphene concentration and enhancement in boiling performance.
- Identified 0.1% graphene as the optimum concentration for thermal enhancement.
- Learned the importance of nanoparticle stability and dispersion techniques for consistent performance.
- Developed skills in both experimental fluid dynamics and AI-based simulation.
- Gained experience in using graph plotting, thermocouples, high-speed imaging, and MATLAB neural network tools.
- Understood the impact of wettability, surface properties, and nucleation dynamics on boiling behavior.
- Strengthened knowledge of thermal systems, heat exchangers, and material-fluid interaction.

Future Scope

Future work can focus on long-term stability and reusability of graphene nanofluids, especially at higher concentrations. While current dispersion techniques worked well for short experiments, industrial applications require long-lasting, stable suspensions.

Further enhancement can be explored by using hybrid nanoparticles like graphene-MWCNT or graphene-metal oxides, which may provide better synergy.

More in-depth studies can analyze the effect of surface roughness, coatings, and fluid flow orientation on boiling behavior. The use of advanced surface treatments and textured heater surfaces could further increase nucleation and enhance heat transfer.

Numerical simulations can be expanded using CFD models to visualize flow and temperature fields during boiling. The AI models developed can be refined using larger datasets and multi-variable optimization to predict performance for different fluids and geometries.

Lastly, this work opens opportunities to implement graphene nanofluids in real-world heat exchangers, cooling systems, and green energy solutions, particularly where space-saving and efficient thermal management is essential.