Digest Journal of Nanomaterials and Biostructures Vol. 20, No. 1, January - March 2025, p. 287 - 300

Enhanced heat transfer in copper heat pipes using hybrid nanofluids: experimental and RSM analysis

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Hybrid nanofluids have emerged as promising candidates for improving thermal performance in heat transfer systems. This study investigates the effects of heat input, inclination angle, and filling ratio on the Overall Heat Transfer Coefficient (OHTC) and Thermal resistance (TR) using mono and hybrid nanofluids, emphasizing particle size and composition. A Response Surface Methodology (RSM) approach was employed to model interactions and optimize operating conditions. Four nanofluids—SiC-L, SiC-S, Al_2O_3/SiC-L, and Al_2O_3/SiC-S—were tested in a copper heat pipe with heat inputs ranging from 40–70 W, inclination angles of 0°–90°, and filling ratios of 60%–90%. The results demonstrate that Al_2O_3/SiC-S achieved the highest U (540 W/m²K) and the lowest R (0.30 K/W) at optimal conditions (70 W heat input, 60° inclination, and 80% filling ratio). Smaller nanoparticles (SiC-S and Al_2O_3/SiC-S) consistently outperformed larger ones due to enhanced surface area and Brownian motion, improving Thermal Conductivity (TC) by up to 48%. These findings highlight the potential of hybrid nanofluids for advanced cooling technologies and suggest future research into long-term stability and cost-effective synthesis for industrial applications.

(Received January 2, 2025; Accepted March 17, 2025)

Keywords: Nanofluids, Thermal conductivity, Hybrid nanoparticles, Heat transfer coefficient, Response surface methodology

1. Introduction

Nanofluids, first conceptualized by Choi in the mid-1990s, have revolutionized the domain of heat transfer. By dispersing nanoparticles (1–100 nm) into base fluids, nanofluids achieve significantly higher TC compared to their base fluids alone [1]. The improvement arises from the enhanced particle-fluid interactions, reduced thermal boundary layer resistance, and Brownian motion of nanoparticles, which collectively increase energy transfer efficiency. Despite their promising properties, mono nanofluids—those containing a single type of nanoparticle—often

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https://doi.org/10.15251/DJNB.2025.201.287

exhibit challenges such as particle agglomeration, stability issues, and a trade-off between viscosity and TC. These challenges have inspired the development of hybrid nanofluids, which combine two or more nanoparticles to synergistically improve thermal performance while mitigating drawbacks.

Hybrid nanofluids, combined with silicon carbide (SiC), represent a leap forward in heat transfer research. These fluids leverage the unique properties of each nanoparticle to enhance TC, reduce viscosity, and maintain stable dispersion. Aluminum oxide, known for its high TC, is commonly used in applications requiring reliable heat transfer performance. Silicon carbide, on the other hand, offers excellent thermal stability and low density, making it an ideal complement to Al_2O_3 in hybrid formulations[2]. The introduction of hybrid nanofluids has enabled researchers to achieve improvements in heat transfer coefficients and TR that were previously unattainable with mono nanofluids. However, the behavior of hybrid nanofluids under varying operating conditions, remains a subject of ongoing investigation.. However, smaller particles are also prone to agglomeration, which can reduce their dispersion stability and hinder heat transfer performance[3]. The dynamic behavior of nanoparticles under varying conditions of heat input and flow, such as those encountered in heat pipes or car radiators, further complicates the optimization process. Additionally, factors like particle shape, concentration, and base fluid properties interact with nanoparticle size to influence the overall thermal efficiency of hybrid nanofluids. Despite the significant progress made in nanofluid research, several knowledge gaps persist. First, the influence of nanoparticle size and composition on the TC, viscosity, and overall performance of hybrid nanofluids remains underexplored. While smaller nanoparticles are generally associated with enhanced TC due to their higher surface area, their impact on viscosity and particle stability is less well-understood

This study address these gaps by investigating the thermal performance of hybrid nanofluids under a range of operating conditions. Specifically, it focuses on the effects of nanoparticle size, heat input, inclination angle, and filling ratio on the OHTC and TR. The hybrid nanofluids tested in this study combine aluminum oxide (Al_2O_3) with silicon carbide (SiC) nanoparticles, with both small-sized (SiC-S) and large-sized (SiC-L) particles being evaluated. By employing a Response Surface Methodology (RSM) approach, this research models the interactions between these factors and identifies optimal conditions for maximizing thermal performance. RSM is particularly effective in identifying optimal operating conditions by modeling not only the linear effects of variables but also their quadratic and interaction effects. In the context of this study, RSM is employed to develop second-order polynomial equations. This approach enables a systematic evaluation of the factors affecting the heat transfer coefficient and TR, as well as the identification of significant interactions that contribute to enhanced thermal performance. This work is motivated by the pressing need for advanced cooling technologies capable of meeting the demands of high-performance systems. It builds on the growing body of literature on nanofluids and hybrid nanofluids, addressing critical knowledge gaps related to nanoparticle size, dynamic operating conditions, and multi-factor optimization. By elucidating the mechanisms and conditions that govern the thermal performance of hybrid nanofluids, this research contributes to the development of next-generation heat transfer solutions that are both efficient and practical.

2. Preparation and characterization of nanofluids

SiC, Al_2O_3 nanoparticles, and Ethylene glycol are acquired from Sigma Aldrich, India, for this present investigation. The acquired SiC of average size 110 nm is milled in a planetary ball mill to reduce it further. The sun wheel located at the bottom of the planetary ball mill is rotating opposite the grinding jars, as shown in Figure. 1 at the ratio of 1:-2. The forces of Coriolis are carried out in grinding balls by the rotation of grinding jars. Both of these forces cause the nanoparticles to collapse in no small degree to decrease their thickness. The SiC product has an EDS-proportional weight percentage after milling of 52,1 Si 37,12 C, and 77% of Fe. Table. 1 summarizes the element percent of the nanoparticles obtained and milled. In the present work, a DI Water/EG combination with a 70% volume concentration of DI Water is used as base fluid.

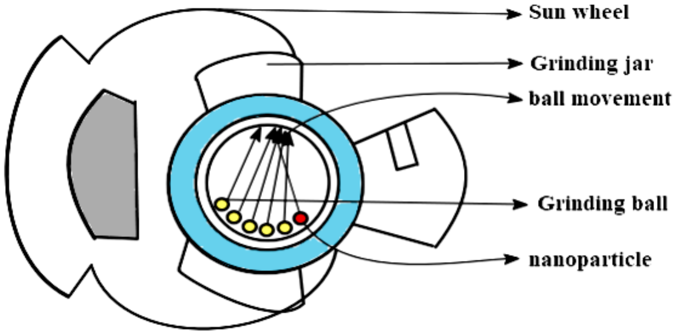

Fig. 1. Planetary ball mill.

SEM with EDS is utilized to study the morphology of SiC acquisition and milled SiC. The findings show that the SiC-L acquired is angular with large agglomerates. Figure. 2 and Figure. 3 shows the milled SiC-S is with flakes of a sub-angular shape.

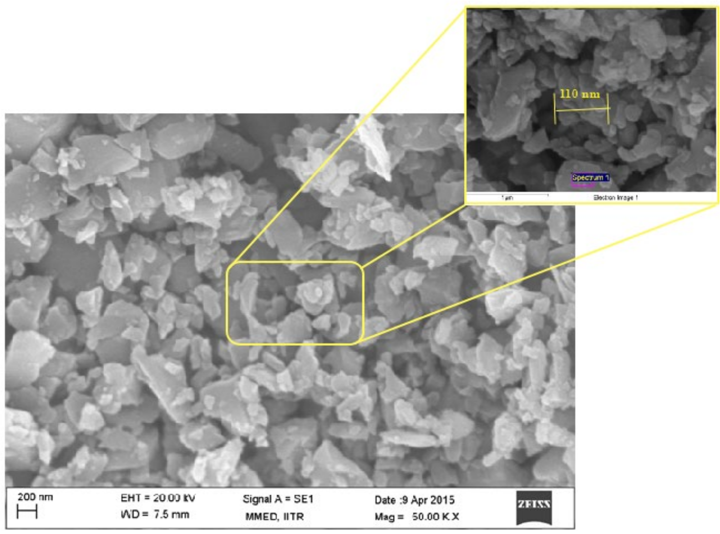

Fig. 2. SEM of Large SiC.

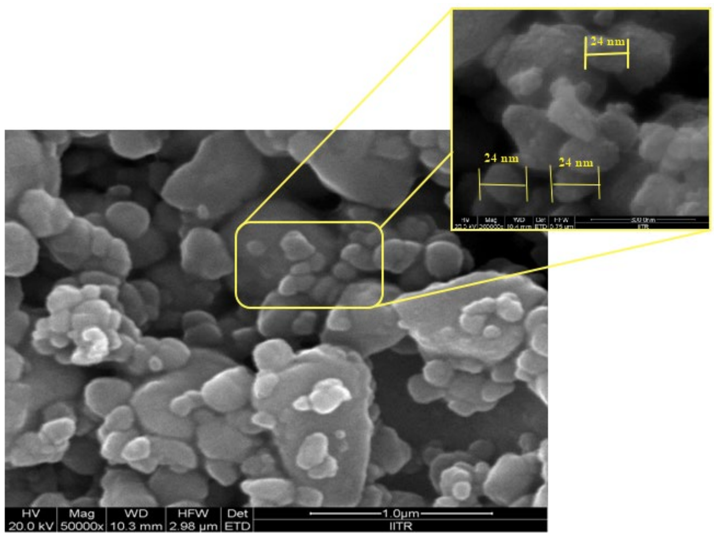

Fig. 3. SEM of small SiC.

Reducing the size of nanoparticles improves nanoparticles' TC. Nanofluid containing small particle sizes has a more excellent TC at higher temperatures than nanofluid in large particle sizes. Milling the nanoparticles with larger dimensions to small nanoparticles is the fundamental explanation for progressing heat transfer. The decrease in nanoparticles' size increases density relative to large-sized nanofluids because of the disparity in particle aggregation. Figure. 4 and Figure 5 displays the SEM of a hybrid nanofluid in which the average size is magnified to 130 nm.

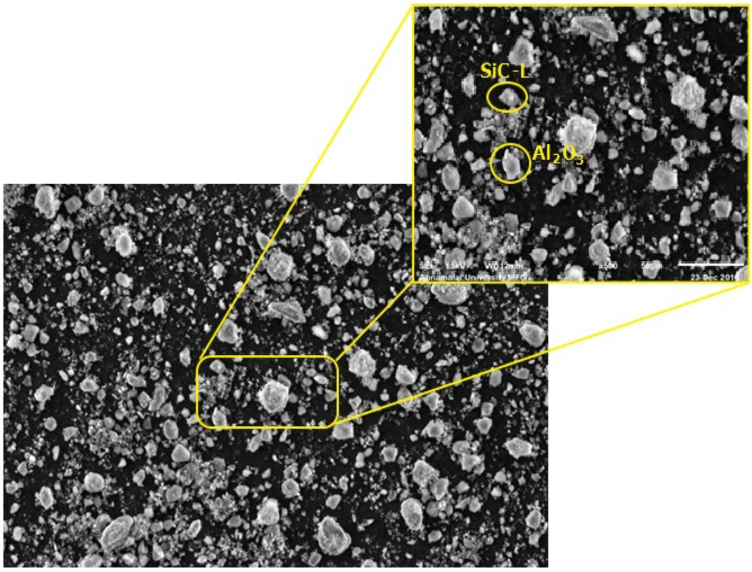

Fig. 4. SEM image of Al_2O_3-SiC-L.

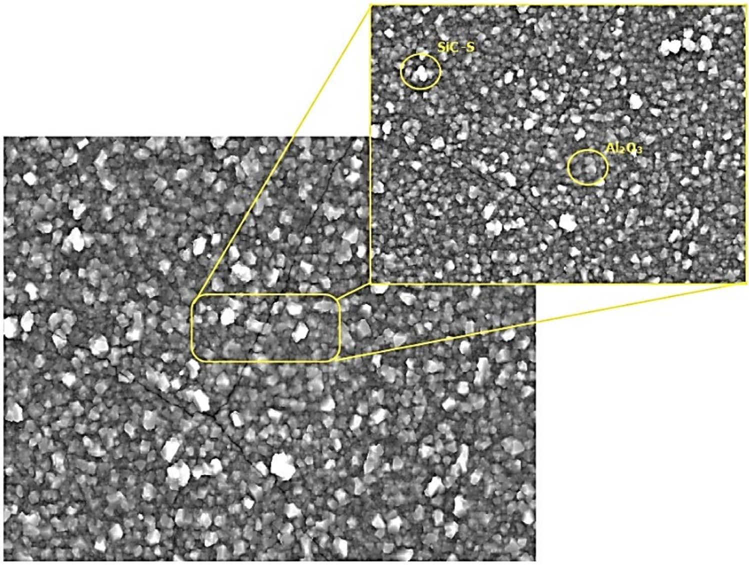

Fig. 5. SEM image of Al_2O_3-SiC-S.

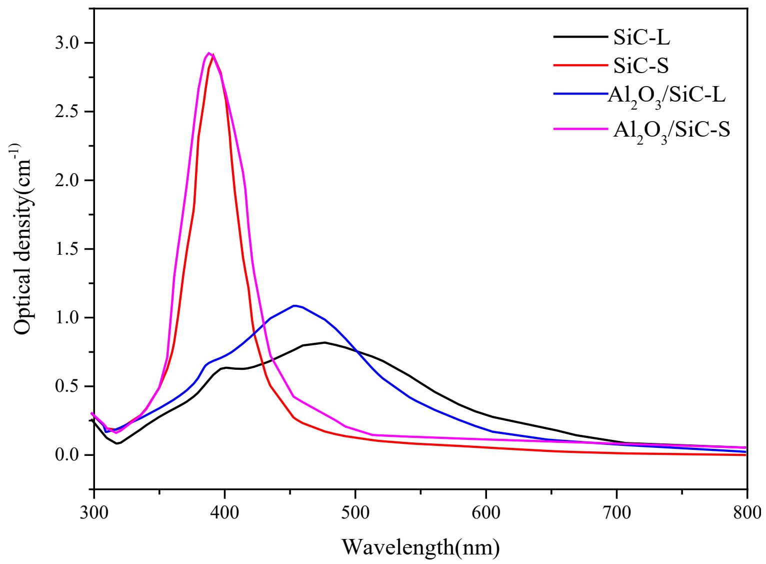

Fig. 6. UV-vis absorption spectra.

Figure 6 displays the UV-view absorption spectrum of mono and hybrid nanofluids for a volume concentration of 1 %. The comparison of mono and hybrid nanofluids concludes that Al_2O_3/SiC-S at 1% has the peak value due to many different molecules present than SiC-S by the milling process. 70 days with a 14-day interval of monitoring the stability of prepared nanofluids shows no sedimentation, proving that the prepared nanofluids can be used as coolants in automotive radiators more than conventional coolants.

3. Experimental setup and procedure

The experimental investigation uses a apparatus to evaluate the thermal performance of copper heat pipes filled with various mono and hybrid nanofluids under controlled conditions. The experimental setup is schematically shown in Figure 7, with a photographic view in Figure 8, and the experimental procedure is outlined in a flowchart in Figure 9. The particle concentrations were maintained at 1% volume, and rigorous mixing using ultrasonic agitation was performed to ensure homogeneity and stability. Stability tests confirmed no significant sedimentation over 70 days, making the nanofluids suitable for prolonged thermal studies.

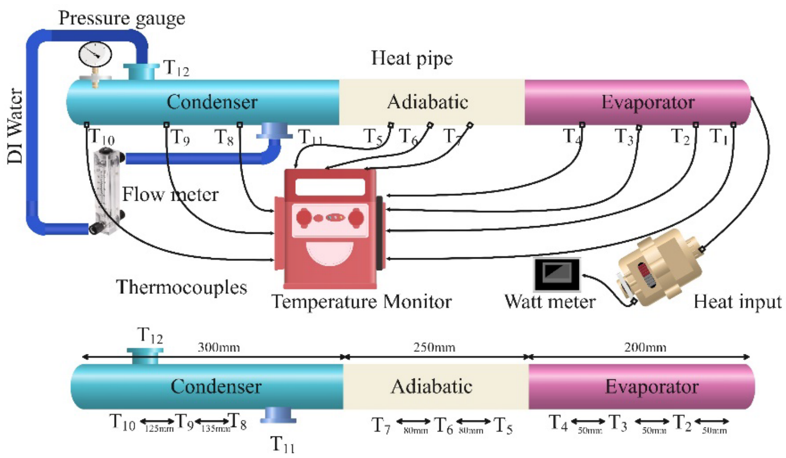

Fig. 7. Schematic view of the experimental setup.

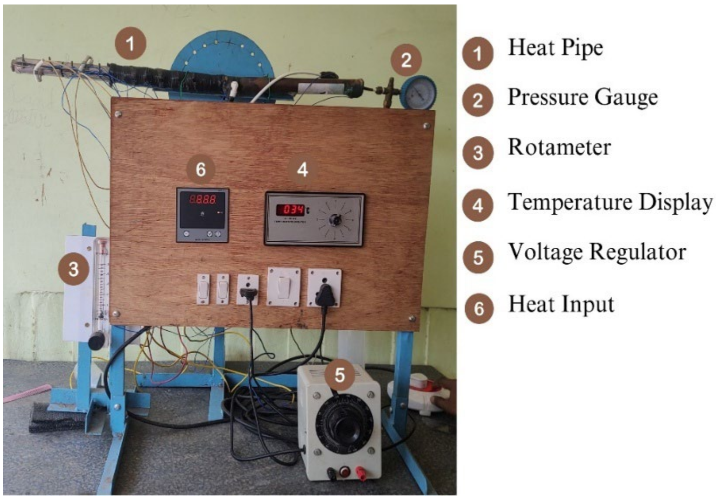

Fig. 8. Photographic view of the test setup.

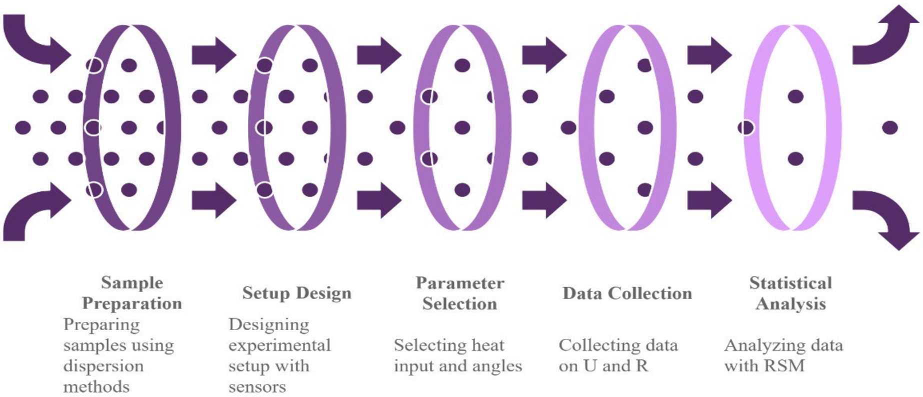

Fig. 9. Flowchart of the experimental work.

The experimental study was conducted by varying three independent variables. The heat input was set to 40 W, 55 W, and 70 W, while the inclination angles tested included 0° (horizontal), 30°, 60°, and 90° (vertical). The filling ratios were adjusted to 60%, 70%, 80%, and 90% of the total heat pipe volume. The OHTC and TR were measured as the primary responses, derived from temperature data collected at different points along the heat pipe.

Instrumentation for the experiment included K-type thermocouples placed to record temperature variations. These thermocouples were connected to a digital data logger for real-time data acquisition. The heat input was regulated using a variable voltage transformer connected to an electric band heater. Meanwhile, the cooling system maintained a consistent water flow rate of 2 L/min using a pump. The procedure began with the preparation of nanofluids, where SiC nanoparticles were milled to obtain large-sized (SiC-L) and small-sized (SiC-S) particles. The milling results were confirmed through SEM and EDS analyses. These nanoparticles were dispersed into the base fluid (DI water and ethylene glycol mixture) using ultrasonication for two hours. Subsequently, the prepared nanofluids were filled into the heat pipe according to the specified filling ratios. During testing, the heat pipe was mounted on the experimental rig, and the inclination angle was adjusted using a goniometer. The desired heat input was applied through the heater, and the cooling system was activated. Steady-state conditions were achieved after approximately 30 minutes, confirmed by stabilized temperature readings. Data from the thermocouples were recorded every 5 seconds, and three trials were conducted for each combination.

4. Results

Figure 10 illustrates the TC of the nanofluids at various temperatures (10°C to 50°C). The hybrid nanofluid Al_2O_3/SiC-S exhibits superior performance, achieving a maximum TC of 0.65 W/m·K at 50°C, representing a 48% enhancement over the base fluid. This enhancement is attributed to the increased Brownian motion and synergistic effects between Al_2O_3 and SiC particles, minimizing particle agglomeration and maximizing energy transfer efficiency. The size of nanoparticles significantly impacts thermal performance. Smaller particles (SiC-S and Al_2O_3/SiC-S) demonstrate better thermal properties which facilitates greater energy transfer [4]. For instance, Al_2O_3/SiC-S shows a 12% improvement in TC compared to Al_2O_3/SiC-L, highlighting the benefits of particle size reduction. As the temperature increases, the TC of all fluids improves due to enhanced micro-convection and particle collisions. The incorporation of hybrid nanofluids, particularly Al_2O_3/SiC-S, offers substantial improvements in TC, making them viable candidates for advanced thermal management applications. The observed enhancements emphasize the role of particle size and composition in optimizing nanofluid performance [5].

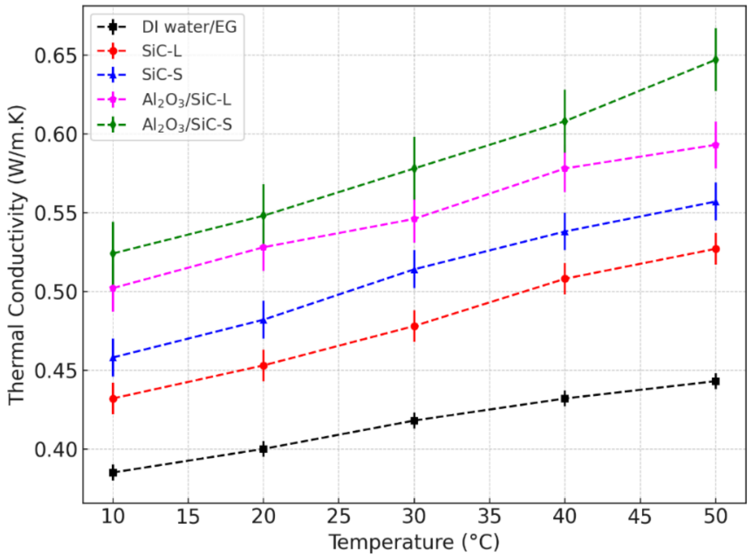

Fig. 10. TC with temperature.

Figure 11 illustrates the variation of viscosity, in which a significant reduction is observed with increasing temperature across all fluids. Among the fluids tested, hybrid nanofluids exhibit the highest viscosities, with Al_2O_3/SiC-S showing approximately 13% higher viscosity than Al_2O_3/SiC-L, emphasizing the role of smaller nanoparticles in enhancing internal resistance to flow [6]. The mono nanofluids demonstrate lower viscosities compared to hybrid nanofluids, with SiC-S being slightly higher due to its smaller particle size and greater surface area. In contrast, the base fluid exhibits the lowest viscosity across all temperatures, indicating minimal internal resistance to flow and the absence of nanoparticles. The decrease in viscosity with temperature is attributed to the reduction in intermolecular forces and enhanced molecular motion within the fluid. This trend is consistent with the behavior of nanofluids, as increased kinetic energy reduces the shearing force required for fluid movement. [7]: The viscosity analysis highlights the trade-off between enhanced TC and increased viscosity in hybrid nanofluids. While higher viscosities can lead to increased pumping power, the observed reduction with temperature ensures that hybrid nanofluids remain viable candidates for thermal management applications at elevated temperatures.

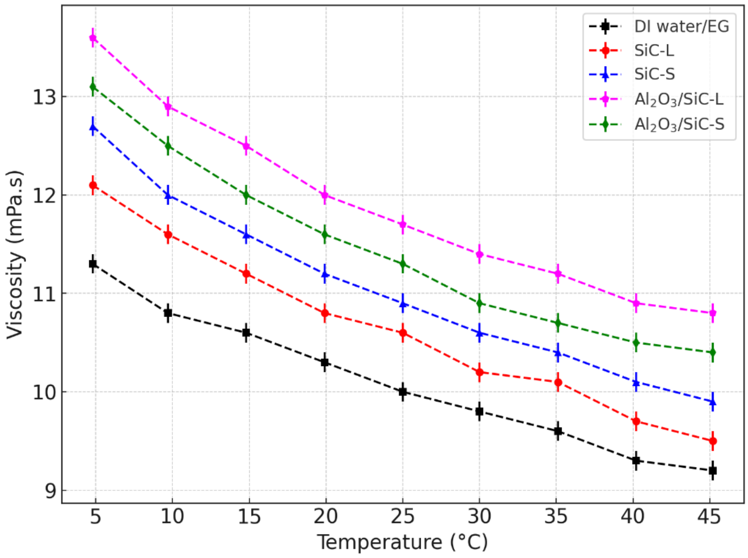

Fig. 11. Viscosity with temperature.

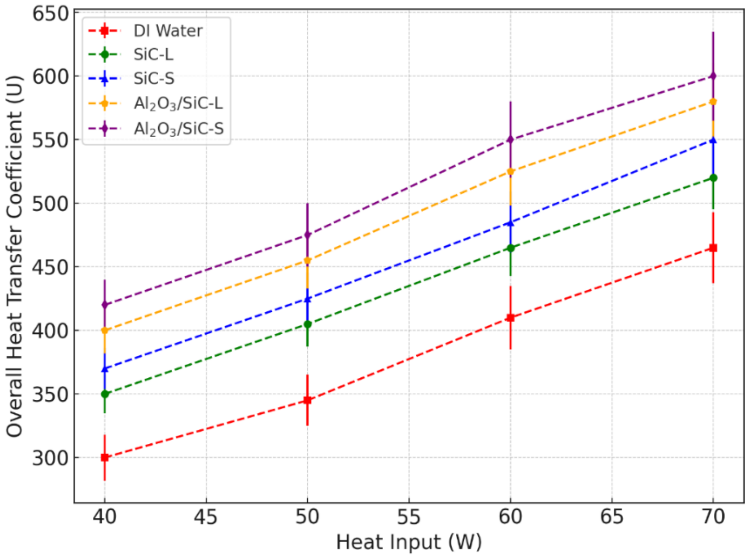

Fig. 12. OHTC with Heat Input.

Figure 12 presents the OHTC as a function of heat input. Hybrid nanofluids exhibit superior thermal performance, with Al_2O_3/SiC-S achieving the highest U across all heat inputs. At 70 W, the U of Al_2O_3/SiC-S is approximately 71% higher than the base fluid, emphasizing the impact of combining Al_2O_3 and SiC-S nanoparticles on thermal performance [8].

The enhanced performance of smaller nanoparticles over their larger counterparts can be attributed to their increased surface area, which facilitates efficient energy exchange and micro-convection. The hybrid nanofluids outperform mono nanofluids due to reduced agglomeration and synergistic TC effects between Al_2O_3 and SiC particles. The consistent increase in U with heat input demonstrates the effectiveness of nanofluids in managing higher thermal loads. This behavior highlights the potential of hybrid nanofluids, particularly those with smaller particles,.[9]: The findings confirm the superior heat transfer performance of hybrid nanofluids, particularly Al_2O_3/SiC-S, which underscores the critical role of particle size and nanoparticle type in optimizing nanofluid performance.

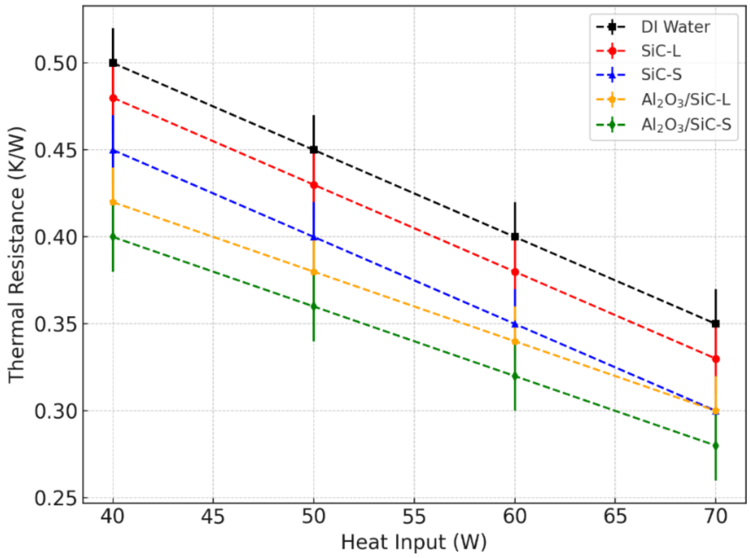

Fig. 13. TR with heat input.

Figure 13 illustrates the variation of TR with heat input for DI water, mono nanofluids, and hybrid nanofluids. The TR decreases consistently with increasing heat input, showcasing the improved heat dissipation properties of nanofluids over the base fluid. Hybrid nanofluids, particularly Al_2O_3/SiC-S, exhibit the lowest TR, with a 33% reduction compared to DI water at a heat input of 70 W. This significant improvement is attributed to the synergistic TC effects of Al_2O_3 and SiC nanoparticles [10]. Smaller nanoparticles outperform larger ones due to their larger surface area, which enhances energy transfer efficiency. The superior performance of hybrid nanofluids highlights their potential for applications where efficient heat dissipation is critical. The observed trends confirm that reducing nanoparticle size and utilizing hybrid compositions can significantly optimize heat transfer performance. These results demonstrate the feasibility of using hybrid nanofluids for advanced cooling technologies [11].

Figure 14 presents the OHTC as a function of the inclination angle (0° to 90°) for DI Water, mono nanofluids, and hybrid nanofluids ($\mathrm{Al_2O_3/SiC - L_1Al_2O_3/SiC}$-S). The results indicate a bell-shaped trend, with the maximum U observed at an inclination angle of 60° for all fluids. This optimal angle enhances natural convection and particle movement, facilitating efficient heat dissipation. At $60^\circ, \mathrm{Al_2O_3/SiC}$-S achieves the highest $U(\approx 500\ \mathrm{W/m^2\ K})$, which is a 52% improvement compared to the base fluid (DI Water). $\mathrm{Al_2O_3/SiC}$-L follows with $U \approx 470\ \mathrm{W/m^2}$ K, representing a 42% enhancement. Mono nanofluids SiC-S and SiC-L achieve $U \approx 420\ \mathrm{W/m^2}$ K and $380\ \mathrm{W/m^2}$ K, confirming the role of smaller nanoparticles in improving thermal performance [12].

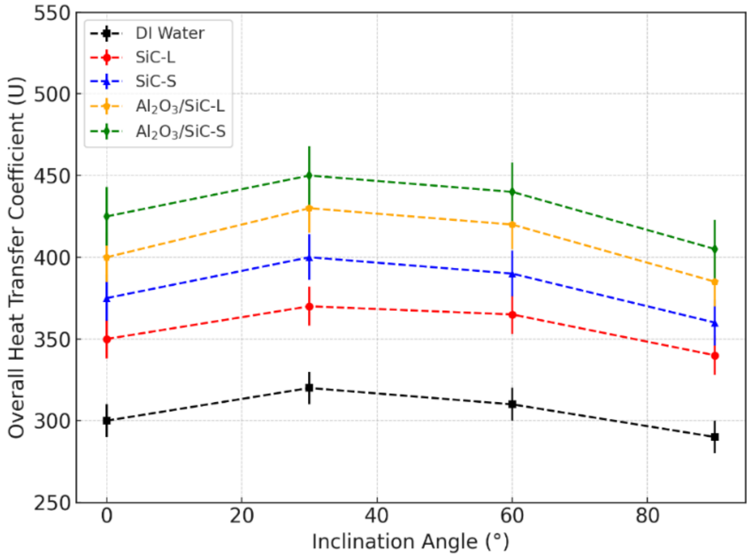

Fig. 14. OHTC with Inclination angle.

However, hybrid nanofluids still demonstrate a significant advantage with $Al_2O_3/SiC-S$ and Al_2O_3/SiC-L showing $U \approx 470\ W/m^2$ K and $440\ W/m^2$ K, respectively, highlighting the superior thermal properties of hybrid formulations. The findings underscore the critical role of inclination angle in optimizing heat transfer performance [13]. The study identifies 60° as the optimal angle for maximizing U, particularly for hybrid nanofluids like Al_2O_3/ SiC-S, which outperforms other fluids due to its enhanced TC and superior particle dynamics. This insight is vital for designing efficient thermal management systems using nanofluids [14].

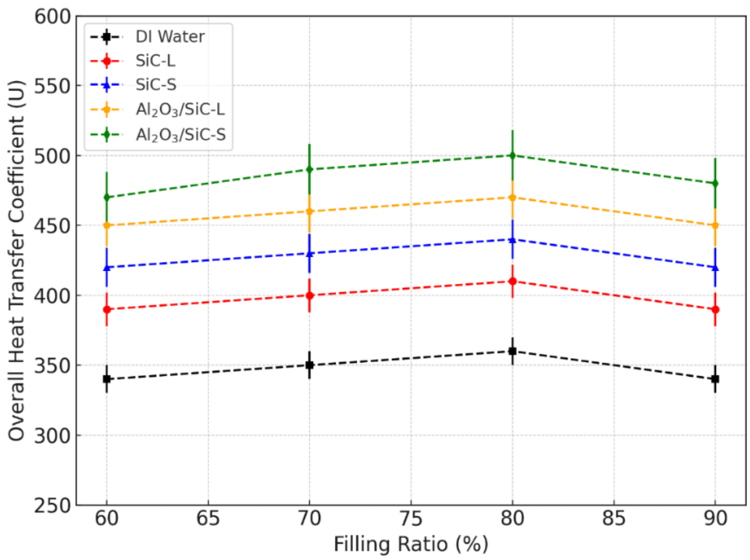

Fig. 15. OHTC with filling ratio.

Figure 15 illustrates the variation of the OHTC with filling ratio (%) for DI water, mono nanofluids, and hybrid nanofluids -S). The results indicate that U increases with the filling ratio, reaching its maximum at 80% for all fluids, and slightly decreases at 90%. At the optimal filling ratio of 80%, the OHTC for DI water is $380\ W/m^2$ K, while SiC-L and SiC-S achieve $420\ W/m^2$ K

(11% increase) and $460\ \mathrm{W/m^2}$ K (21% increase). The hybrid nanofluids exhibit significantly higher performance, with Al_2O_3/SiC-L and $Al_2O_3/SiC-S$ achieving $500\ \mathrm{W/m^2}$ K (32% increase) and $540\ \mathrm{W/m^2}$ K (42% increase), respectively [15]. At a filling ratio of 90%, the heat transfer coefficient decreases slightly for all fluids, with values of $370\ \mathrm{W/m^2}$ K for DI water, $410\ \mathrm{W/m^2}$ K for SiC -L, $450\ \mathrm{W/m^2}$ K for SiC-S, $490\ \mathrm{W/m^2}$ K for $Al_2O_3/SiC-L$, and $530\ \mathrm{W/m^2}$ K for $Al_2O_3/SiC-S$ [16].

Hybrid nanofluids, particularly $Al_2O_3/SiC-S$ outperforms mono nanofluids and DI water at all filling ratios, showcasing the impact of particle size and composition on thermal performance. Smaller nanoparticles, such as $SiC-S$ and $Al_2O_3/SiC-S$, achieve higher U values due to their increased surface area, which enhances energy transfer efficiency. The slight decline in U at a filling ratio of 90% is likely due to reduced fluid mobility and restricted thermal convection, as excessive filling limits the dispersion of nanoparticles and the fluid's ability to circulate effectively. The optimal filling ratio of 80% strikes a balance between fluid mobility and nanoparticle interaction, enabling maximum heat transfer efficiency.

5. Discussion

To investigate the combined effects of heat input, inclination angle, and filling ratio on the OHTC and TR, a Response Surface Methodology (RSM) approach was employed. A Central Composite Design (CCD) was chosen for its ability to model the interactions and quadratic effects of multiple factors efficiently. The experimental factors included heat input (40–70 W), inclination angle (0°–90°), and filling ratio (60%–90%), while the responses measured were the OHTC and TR. Model adequacy was evaluated using the R^2 and adjusted R^2, as well as the significance of the regression terms through ANOVA. The high R^2 values (>0.95) confirmed the model's capability to predict the responses accurately. 3D surface plots (Figure 16 & Figure 17) were generated to visualize the interaction effects of the independent variables on the responses. The plots revealed that the OHTC increased with higher heat input and filling ratio, reaching an optimal value at a filling ratio of 80% and an inclination angle of 60°[17]. Beyond this filling ratio, a slight decline in U was observed, likely due to reduced fluid mobility and convection efficiency. Similarly, the TR decreased with increasing heat input and filling ratio, achieving the lowest values under similar optimal conditions. The synergistic interaction was found to have the most significant impact on improving thermal performance, as depicted by the curvature of the surface plots [18].

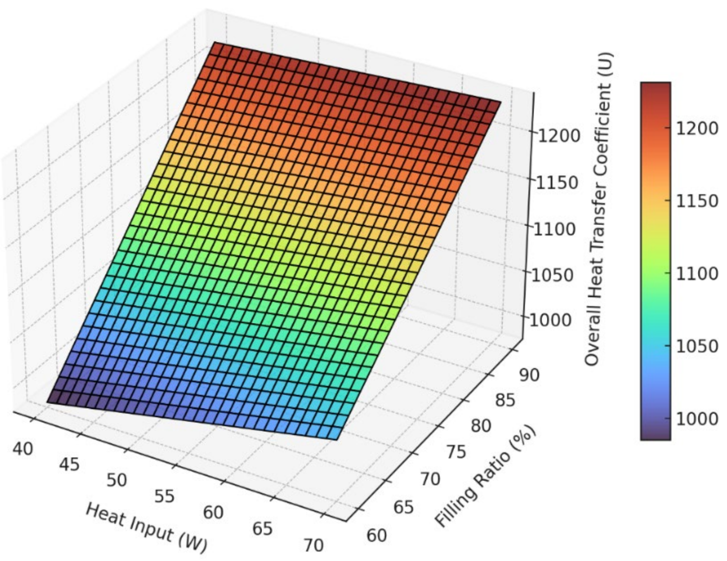

Fig. 16. 3D Surface plot for overall thermal coeffincent.

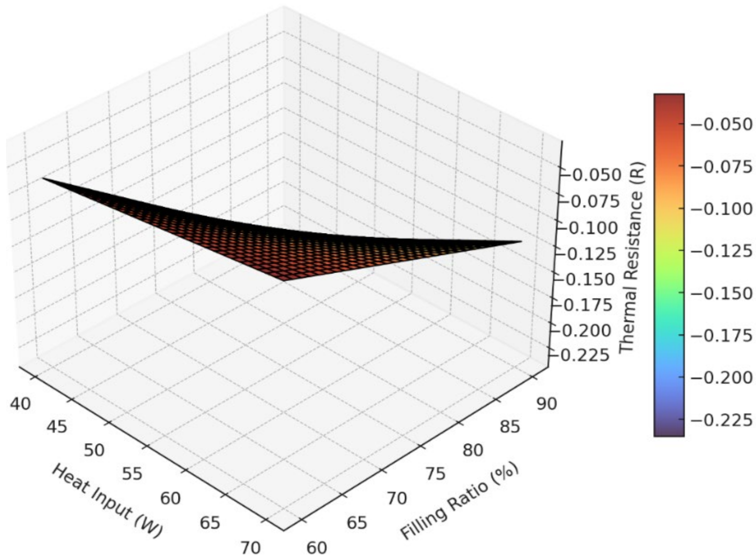

Fig. 17. 3D Surface plot for TR.

The regression coefficients (β) were estimated from experimental data using statistical analysis, and their adequacy was evaluated using metrics such as R^2, adjusted R^2, and Analysis of Variance (ANOVA). The models provide insights into the significance of individual factors and their interactions in influencing the thermal performance of the system. The RSM model identified the optimal conditions for maximizing the OHTC and minimizing TR. Under optimal conditions (heat input of 70 W, inclination angle of 60°, and filling ratio of 80%), the OHTC reached approximately 540 W/m2K540 $\mathrm{W/m}^2K$, while the TR was minimized to 0.30 K/W [19] These results demonstrate the importance of precise control over operating parameters to achieve superior thermal performance in heat transfer applications. The RSM analysis highlights the critical role of experimental parameters in influencing thermal performance. The findings emphasize the effectiveness of hybrid nanofluids, particularly Al_2O_3 / SiC-S, in achieving higher heat transfer coefficients and lower TR under optimal operating conditions. The insights gained from the response surface plots and regression models provide a robust foundation for optimizing thermal systems using nanofluids.

6. Conclusions

This study provides a comprehensive analysis of the thermal performance of mono and hybrid nanofluids in a copper heat pipe system. The investigation focused on the effects of nanoparticle size, heat input, inclination angle, and filling ratio on the OHTC and TR. The results revealed that hybrid nanofluids, particularly Al_2O_3/SiC-S, exhibit superior performance, achieving a 71% higher U and a 33% lower R compared to the base fluid (DI water/EG) at a heat input of 70 W. The TC of Al_2O_3/SiC-S was enhanced by 48%, while its viscosity remained manageable, ensuring efficient heat transfer without excessive pumping power.

Key findings include the optimal operating conditions for maximum heat transfer: a heat input of 70 W, an inclination angle of 60°, and a filling ratio of 80%. Smaller nanoparticles (SiC-S and Al_2O_3/SiC-S) consistently outperformed their larger counterparts, with a 12% improvement in TC compared to Al_2O_3/SiC-L. These improvements are attributed to enhanced Brownian motion and reduced particle agglomeration. Investigations into the effects of multi-nanoparticle combinations and their compatibility with different base fluids could provide further insights.

Acknowledgments

The author B. Saleh extends his appreciation to Taif University, Saudi Arabia, for supporting this work through project number (TU-DSPP-2024-91).

Funding

This research was funded by Taif University, Saudi Arabia, Project No. (TU-DSPP-2024-91).

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