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EXPERIMENTAL ANALYSIS OF SILVER NANOPARTICLES IN HEAT PIPES: A COMPARATIVE STUDY OF NANOSPHERE AND NANOCUBE MORPHOLOGIES

EKSPERIMENTALNA ANALIZA NANODELCEV SREBRA V TOPLOTNIH IZMENJEVALNIKIH: PRIMERJALNA MORFOLOŠKA ŠTUDIJA MED NANO-KROGLICAMI IN NANO-KOCKICAMI

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Efficient heat transfer is critical in modern thermal management systems, and nanofluids containing nanoparticles have emerged as a promising solution. This study investigates the influence of silver nanoparticle morphology (nanospheres and nanocubes) and volume concentration on the thermal performance of heat pipes. Despite advancements, the role of nanoparticle shape in enhancing heat transfer remains underexplored. This research aims to optimize heat pipe performance by evaluating the effects of nanoparticle shape, concentration, and power input. Using an experimental approach, nanofluids with different concentrations (0.0125–0.1 %) were prepared and tested at power inputs of 40, 70, and 100 kW. Results showed that nanosphere nanofluids exhibited a maximum heat transfer coefficient of 5800 W/m^{2}K, a 38-% improvement over deionized water, while nanocube nanofluids achieved 5500 W/m^{2}K. The thermal efficiency reached its highest value of 72 % for nanospheres at a concentration of 0.1 %. The thermal resistance decreased by 29 % for nanospheres and 25 % for nanocubes at the maximum power input. These findings underscore the importance of morphology in enhancing heat transfer. The above results have implications for industrial heat management systems, offering insights into optimizing nanofluid properties for specific applications. Future work could explore the interaction of particle size and morphology with different base fluids to further refine performance.

Keywords: nanofluids, silver nanoparticles, heat transfer, nanosphere/nanocube comparison, heat pipe optimization

Učinkovit prenos toplote je pomemben za delovanje modernih toplotnih sistemov (izmenjevalnikov toplote oz. rekuperatorjev). Nanokapljevine, ki vsebujejo nanodelce predstavljajo obetajočo rešitev za njihovo izboljšanje. V tem članku avtorji opisujejo študijo vpliva morfologije srebrnih delcev (nanokroglic in nanokockic) in njihovega volumskega deleža na termične lastnosti kapljevin v toplotnih izmenjevalnikih. Kljub nedvomnim prednostim pa vpliv oblike nanodelcev v naprednih toplotnih sistemih še ni bil raziskan. V tej raziskavi so se avtorji posvetili optimizaciji lastnosti toplotnih izmenjevalnikov z ovrednotenjem vpliva oblike nanodelcev, njihove koncentracije in vnosa toplotne energije. Z uporabo eksperimentalnega pristopa so avtorji pripravili nanokapljevine z različno vsebnostjo nanodelcev (0,0125 % do 0,1 %) in različnimi vnosi moči 40, 70 in 100 kW. Rezultati preizkusov so pokazali, da je bil dosežen maksimalni koeficient prenosa toplote 5800 W/m^{2}K pri nanokapljevini, ki je vsebovala nanokroglice. To predstavlja 38 % izboljšanje v primerjavi z uporabo deionizirane vode. Pri uporabi srebrnih nanokockic pa so avtorji dosegli nekaj manjši koeficient prenosa toplote 5500 W/m^{2}K. Toplotna učinkovitost je bila največja (72 %) pri 0,1 % koncentraciji nanokroglic. Toplotna upornost je bila 29 %-na pri nanokroglicah in 25 %-na pri nanokockicah ter vnosu toplote z maksimalno močjo. S temi raziskavami so avtorji potrdili pomembnost morfologije in koncentracije nanodelcev za izboljšanje koeficienta prenosa toplote. Rezultati raziskave ponujajo vpogled v optimizacijo lastnosti nano tekočin, ki so pomembni za izdelavo novih modernih industrijskih izmenjevalnikov toplote. V prihodnosti avtorji nameravajo raziskati še interakcijo med velikostjo delcev in njihovo morfologijo za različne vrste kapljev z namenom nadaljnje optimizacije oziroma izboljšanja.

Ključne besede: nanokapljevine, srebrni nanodelci, prenos toplote, primerjava med nano kroglicami in nano kockicami, optimizacija toplotnega izmenjevalnika

1 INTRODUCTION

The quest for enhanced thermal management systems has gained significant momentum in recent years, driven by the demands of advanced industrial processes, electronic cooling, and energy efficiency. At the heart of these innovations lies the heat pipe, an efficient thermal transport device widely used for its capability to transfer heat with minimal temperature gradients. The effectiveness of heat pipes depends largely on the thermal properties of the working fluid, prompting researchers to explore novel approaches for performance enhancement.

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Among these, the integration of nanofluids – fluids containing nanoparticles – has emerged as a revolutionary concept, offering unprecedented opportunities to tailor heat transfer properties.[1]

Nanofluids, first conceptualized in the late 1990s, have rapidly advanced as a frontier in thermal engineering. These engineered fluids combine the base fluid's macroscopic transport capabilities with the exceptional thermal conductivity of nanoparticles. This synergy significantly enhances thermal conductivity, heat transfer coefficients, and overall system efficiency. In particular, silver nanoparticles have garnered attention for their outstanding thermal and optical properties, high electrical conductivity, and superior stability. However, the influence of nanoparticle morphology – such as spherical versus cubic shapes – on heat transfer characteristics remains inadequately explored.[2] Despite extensive studies on nanofluids in heat pipes, the specific role of nanoparticle morphology in influencing thermal performance remains inadequately explored.

Prior research primarily focused on enhancing thermal conductivity through nanoparticle dispersion, yet a detailed comparative analysis of different morphologies was lacking. Additionally, the combined effect of concentration, shape, and operational power on the key thermal performance metrics requires further investigation. This study aims to bridge these gaps by systematically evaluating the impact of nanosphere and nanocube morphologies on heat pipe efficiency, optimizing operating conditions for maximum thermal enhancement. This knowledge gap is critical since the shape of nanoparticles affects their dispersion stability, surface area, and interaction dynamics with the base fluid.

Despite numerous studies on nanofluids, the effects of nanoparticle concentration, shape, and operating conditions on the performance of heat pipes have not been fully elucidated. The variation in findings across different experimental setups and nanoparticle morphologies highlights the need for a systematic investigation.[3] Furthermore, the interplay between nanoparticle-induced enhancements and operating variables, such as power input and heat flux, requires robust optimization techniques to unlock the full potential of nanofluids.[4]

This study addresses these gaps by conducting a comprehensive experimental analysis of heat pipes using silver nanofluids with two distinct nanoparticle morphologies: nanospheres and nanocubes. The research explores the effects of varying nanoparticle concentrations and power inputs on key performance metrics, including the heat transfer coefficient, thermal efficiency, and thermal resistance. To systematically model and optimize these parameters, response surface methodology (RSM) is employed, providing valuable insights into the complex interactions between design variables.[5]

The scalability of nanoparticle synthesis for industrial applications remains an important consideration for real-world implementation. The feasibility of large-scale production must be evaluated to ensure cost-effectiveness while maintaining nanoparticle stability and thermal performance. Additionally, surface coatings play a critical role in preventing agglomeration and enhancing dispersion stability, which directly affects heat transfer efficiency. Investigating different coating materials and their interactions with nanofluids provides valuable insights into optimizing long-term performance in industrial thermal management systems.

By bridging the knowledge gap in nanoparticle morphology and operational optimization, this study aims to provide a clear roadmap for enhancing heat pipe performance. The findings hold significant implications for industrial thermal management systems, enabling the development of highly efficient and customizable solutions tailored to specific applications. Through rigorous experimental methodologies and advanced statistical modeling, this work contributes to advancing the field of nanofluid-based heat transfer technologies, ultimately paving the way for next-generation thermal engineering solutions.

2 MATERIALS AND METHODS

To improve clarity, the experimental methodology was structured into distinct subsections: (i) nanoparticle characterization, (ii) nanofluid preparation and stabilization, (iii) experimental setup and instrumentation, and (iv) data acquisition and processing. The nanoparticle morphology was verified using transmission electron microscopy (TEM), while stability was assessed through a zeta potential analysis. Nanofluids were prepared under controlled conditions, maintaining uniform dispersion via ultrasonication and magnetic stirring. The experimental setup, including the heat pipe, heating element, and temperature sensors, was optimized to minimize external thermal losses. Finally, data acquisition was performed using an automated system with real-time monitoring to ensure accuracy and repeatability. The experimental study was conducted to evaluate the thermal performance of a heat pipe using nanofluids containing silver nanospheres and nanocubes at varying concentrations and power inputs. The materials used, preparation methods, and experimental setup are described in detail below. Silver nanoparticles with spherical and cubic morphologies were utilized for the preparation of nanofluids. The silver nanospheres (a 100-nm diameter) were provided as a PVP-coated aqueous suspension with a hydrodynamic diameter of 126 nm, a zeta potential of -39 mV, and a silver purity of 99.99 %. The particle concentration was $1.8\times10111.8\times10^{11}$ particles/mL, with a mass concentration of 1.08 mg/mL.[6] The nanocubes (a 100-nm diameter) were similarly stabilized with PVP, and suspended in ethanol. They exhibited a hydrodynamic diameter of 166.6 nm, a zeta potential of –10.5 mV, and a particle concentration of

9.9×10109.9×10[10] particles/mL . **Table 1** gives the specification of the heat pipe used in the work.

Table 1: Specifications of the heat pipe

Description	Data
Container material	Copper
Wick material	Stainless steel
Total length of pipe	0.75 m
Evaporator length	0.2 m
Adiabatic length	0.25 m
Condenser length	0.3 m
Outer diameter of the pipe	19×10^{-3} m
Inner diameter of the pipe	17×10^{-3} m
Mesh size per inch	80
No. of strands/m	3145
No. of layers	2
Wick permeability (K)	4.5×10^{-10} m^2
Wick porosity (ε)	0.72
Mesh wire diameter (d)	0.108×10^{-3} m

Heat pipe orientation plays a significant role in influencing fluid circulation, capillary action, and overall thermal performance. Assessing different orientations, such as vertical, inclined, and horizontal configurations, would provide a comprehensive understanding of performance variations. Furthermore, the interaction between the nanoparticle size and morphology warrants further investigation, as variations in these parameters may influence convective and conductive heat transfer mechanisms differently. The incorporation of real-time monitoring data using advanced sensors and data acquisition systems would further enhance the reliability of experimental findings by capturing transient thermal responses.

Nanofluids were prepared by dispersing silver nanospheres and nanocubes into deionized water at specific volume concentrations of (0.0125, 0.025, 0.05, 0.075, and 0.1) %. The required volume of nanoparticle suspension was calculated and mixed with deionized water. To ensure homogeneity, the mixture was subjected to sonication for 30 minutes using a probe sonicator operating at 200 W and a frequency of 20 kHz. Proper dispersion of nanoparticles in the base fluid is critical to achieving optimal thermal performance in nanofluids. This study employed two complementary techniques to ensure effective dispersion of the acquired nanoparticles: ultrasonic agitation and magnetic stirring. Ultrasonic agitation involves the application of high-frequency sound waves to the nanofluid. These sound waves generate cavitation bubbles, which implode and release intense localized forces, breaking up any nanoparticle agglomerates and ensuring uniform dispersion.[7] This method is particularly effective in dispersing nanoparticles that tend to cluster during storage or initial mixing. In this study, ultrasonic agitation was applied for 30–60 min to achieve a homogenous suspension of nanoparticles within the DI water. This process helps maximize the surface area of the nanoparticles in contact with the fluid, thereby enhancing the nanofluid's thermal conductivity and heat transfer properties.

Magnetic stirring was used to maintain the dispersion of the nanoparticles over time, preventing them from settling at the bottom of the container (). A magnetic stirrer creates continuous motion in the fluid by rotating a magnetic bar inside the nanofluid, ensuring the nanoparticles remain in suspension. Magnetic stirring is a gentle method that helps maintain the integrity of the nanoparticles while ensuring that the dispersion achieved through ultrasonication is preserved. The combination of ultrasonic agitation and magnetic stirring allowed for the preparation of stable nanofluids, which were crucial for obtaining reliable and reproducible heat transfer results. In this study, the role of surfactants in enhancing the stability of silver nanofluids was considered to prevent nanoparticle aggregation and sedimentation over time. Polyvinylpyrrolidone (PVP) was utilized as the stabilizing agent due to its strong affinity for silver nanoparticles, forming a protective layer that improved dispersion and minimized clustering. The nanofluid preparation process incorporated a controlled amount of PVP to maintain homogeneity and ensure consistent thermal performance during experimentation. Additionally, to refine the experimental setup and reduce errors, precise temperature calibration of thermocouples was conducted before each trial, ensuring accurate heat

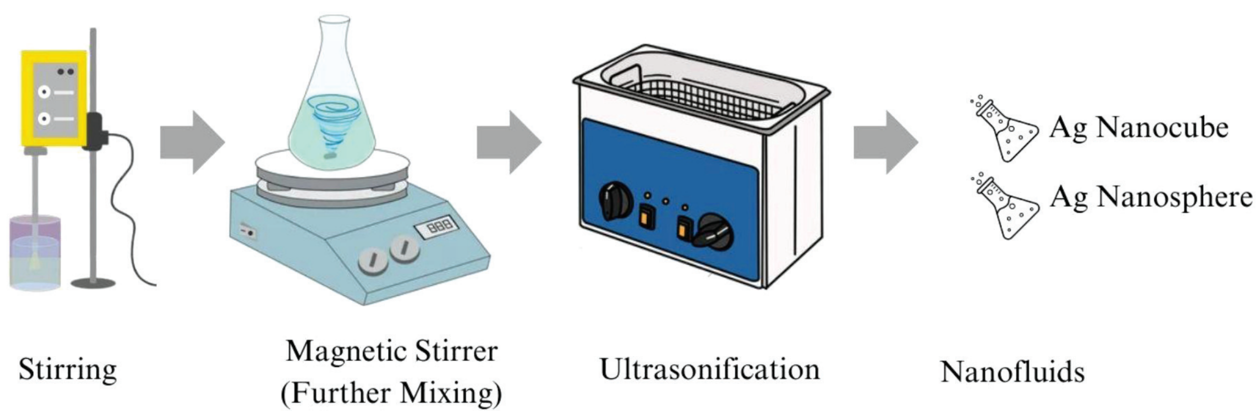

Figure 1: Schematic of nanofluid preparation: nanoparticle dispersion, ultrasonication, and magnetic stirring for uniform suspension stability

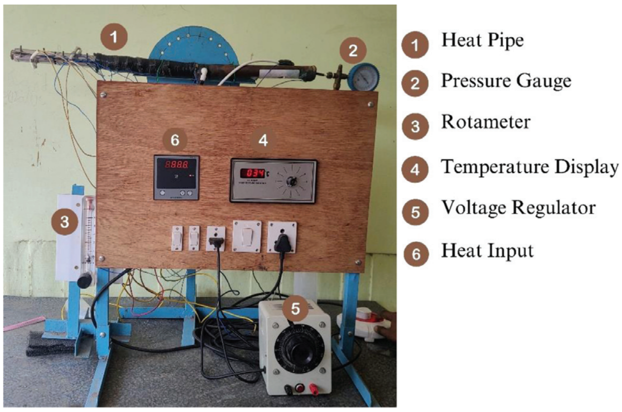

Figure 2: Photographic view of the experimental setup

transfer measurements. Sensor placement was optimized to minimize thermal losses, particularly at the adiabatic section of the heat pipe, while insulation was added around the setup to mitigate external environmental influences. The stability of the nanofluids was confirmed by the absence of visible sedimentation over 24 hours. The long-term stability of nanofluids is a crucial factor in practical applications, as nanoparticle sedimentation can degrade performance over time. A systematic study on sedimentation effects under continuous operation would provide critical insights into nanofluid durability. Additionally, a cost-benefit analysis considering material costs, synthesis complexity, and efficiency improvements would enhance the practicality of implementing nanofluids in industrial heat pipe systems.

The experimental setup, as depicted in **Figure 2**, consisted of a heat pipe system with integrated instrumentation for monitoring and control. The heat pipe, made of copper, had a length of 500 mm and an external diameter of 25 mm. A wick structure was employed inside the heat pipe to facilitate capillary action. A rotameter was installed to regulate the flow rate of cooling water, while a digital pressure gauge monitored the internal pressure. Temperature sensors were placed at the evaporator, adiabatic and condenser sections of the heat pipe to measure local temperatures. A voltage regulator, connected to an electric heater, controlled the power input, which was varied across three levels: 40, 70, and 100 kW. The temperature readings were recorded using a data acquisition system with a temperature display unit. The heat pipe was initially cleaned and vacuumed to remove residual gases. It was subsequently charged with 50 mL of the prepared nanofluid. The charged heat pipe was mounted horizontally, and cooling water was supplied at a constant flow rate of 1.5 L/min to the condenser section. The heat input was provided through the electric heater at the evaporator section and controlled via the voltage regulator. Experiments were conducted at the three power input levels for each volume concentration of the nanofluids. For each condition, the system was allowed to stabilize for 30 min before data collection. Temperature readings were recorded at one-minute intervals for 10 min to ensure repeatability and accuracy. The thermal performance of the heat pipe was analyzed by calculating the heat transfer coefficient and thermal resistance. The heat transfer coefficient was determined using Equation (1):[8]

$$h=\frac{Q}{A\Delta T} \tag{1}$$

where Q is the heat input, A is the heat transfer area, and ΔT is the temperature difference between the evaporator and condenser sections.[9] Thermal resistance was calculated using Equation (2):

$$R=\frac{\Delta T}{Q} \tag{2}$$

where ΔT is the temperature drop across the heat pipe.

The structural and optical properties of the silver nanospheres and nanocubes were characterized using transmission electron microscopy (TEM), UV-Vis spectrophotometry, and dynamic light scattering (DLS). TEM images confirmed the spherical and cubic morphologies, with average diameters of 102 ± 11 nm and 98.5 ± 7 nm for the nanospheres and nanocubes, respectively (**Figure 3**). The zeta potentials indicated good stability for both nanofluids.[10]

To validate the experimental results, the performance of the heat pipe with the nanofluids was compared to that

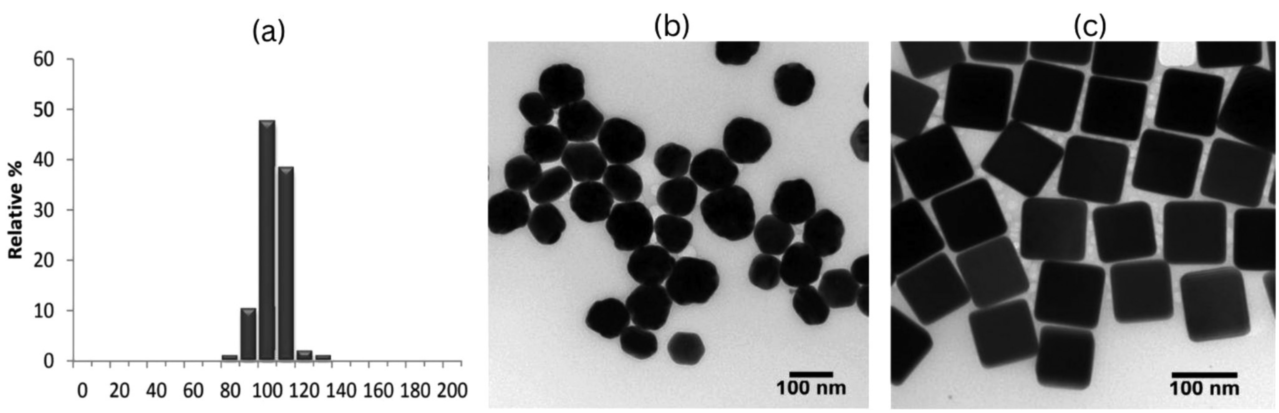

Figure 3: a) Size distribution, b) Ag nanosphere, c) Ag nanocube

with pure water as the working fluid. The repeatability of the experiments was ensured by conducting each test three times, and the standard deviation of the results was found to be less than 5 %. This methodology ensures a robust evaluation of the impact of nanoparticle morphology and concentration on the thermal performance of the heat pipe under different operational conditions.[11] **Table 2** shows the volume concentration and power inputs used in the experiment.

Table 2: Volume concentration and power inputs

Volume concentration (%)	Power (KW)
0	40, 70, 100
0.0125	40, 70, 100
0.025	40, 70, 100
0.05	40, 70, 100
0.075	40, 70, 100
0.1	40, 70, 100

The uncertainty analysis is a vital aspect of experimental studies to ensure the reliability and accuracy of the results. In this study, uncertainties associated with the key parameters including the heat transfer coefficient (HTC), thermal efficiency, and thermal resistance were carefully analyzed. The root-sum-square (RSS) method was employed to estimate the total uncertainty by combining individual uncertainties from all measured parameters.[12] Temperature measurements were conducted using thermocouples with an uncertainty of ±0.5 °C, while power input measurements, controlled using a voltage regulator and wattmeter, had an uncertainty of ±1.5 %. The flow rate, regulated by a rotameter, exhibited an uncertainty of ±2 %.

The total uncertainty in the study was determined using the root-sum-square (RSS) method, which combines individual uncertainties from all measured parameters. To ensure the accuracy of the experimental results, uncertainty propagation was analyzed for each measured parameter, including temperature, power input, and volume concentration. The uncertainty in temperature measurements, recorded using calibrated thermocouples, was estimated at ±0.5 °C, while the power input uncertainty was controlled within ±1.5 % through a regulated voltage supply. Additionally, the flow rate uncertainties were limited to ±2 % using a precision rotameter. The root-sum-square (RSS) method was applied to quantify the total uncertainty across all measured variables, with the heat transfer coefficient uncertainty estimated to be ±3.5 %, thermal efficiency being ±2.8 %, and thermal resistance being ±4.2 %. This rigorous approach ensures the reliability of the reported findings and enhances the reproducibility of the experimental methodology. Equation (3) was used:

$$UR = \sqrt{\sum \left(\frac{\partial R}{\partial x_i} U_{x_i} \right)^2} \quad (3)$$

For the HTC, calculated using the heat input, heat transfer area, and temperature difference between the evaporator and condenser sections, the estimated uncertainty was ±3.5 %. The thermal efficiency, derived from the ratio of useful heat to input heat, showed an uncertainty of ±2.8 %. The thermal resistance, calculated from the ratio of temperature difference to heat input, had an uncertainty of ±4.2 %. These uncertainties were propagated using sensitivity coefficients for each parameter to provide a comprehensive estimate. The primary sources of error included calibration inaccuracies in thermocouples, rotameters, and wattmeters, as well as variations in nanoparticle dispersion stability and environmental factors such as ambient temperature fluctuations.[13] Despite these challenges, the analysis confirmed that the uncertainties in all key parameters were below 5 %, which is within acceptable limits for heat transfer experiments. The experimental setup's robust design and repeated measurements minimized random errors, while systematic errors were mitigated through precise calibration.[14] This comprehensive uncertainty analysis highlights the reliability of the reported findings. It ensures their applicability to both industrial and academic research contexts, providing transparency and confidence in the experimental approach.

3 RESULTS AND DISCUSSION

The experimental analysis of heat pipe performance using silver nanofluids with nanospheres and nanocubes provides crucial insights into their thermal performance, efficiency, and the influence of nanoparticle morphology. The findings are organized to allow an in-depth understanding of the roles of nanoparticle concentration, morphology, and power input. The results include key numeric interpretations and shape-dependent effects.

Figure 4 shows the heat transfer coefficient (HTC) of the heat pipe at different power inputs for deionized (DI) water, nanosphere nanofluid, and nanocube nanofluid. The results indicate that the HTC increases with higher

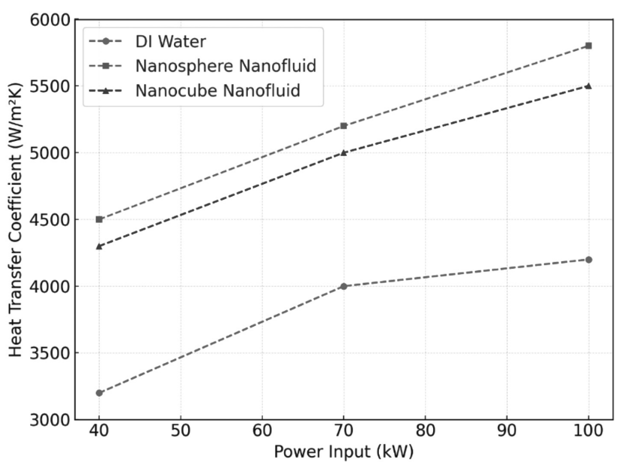

Figure 4: HTC with power input

power inputs in all cases. For DI water, the HTC rises from 3200 W/m²K at 40 kW to 4200 W/m²K at 100 kW.[15] This enhancement is modest compared to nanofluids. The nanosphere-based nanofluid achieves an HTC of 5800 W/m²K at 100 kW, which is a 38-% improvement over DI water. Similarly, the nanocube nanofluid reaches 5500 W/m²K, showing a 31-% increase. The enhanced HTC for nanospheres can be attributed to their higher surface area and uniform dispersion, causing better thermal conductivity. Nanocubes, although less effective at lower concentrations, generate higher turbulence due to their shape, compensating for performance losses at higher power levels.[16] These findings underscore the importance of particle morphology in thermal performance, with nanospheres allowing better thermal interaction and nanocubes contributing to convective heat transfer enhancement.

A distinct difference in heat transfer performance was observed between nanospheres and nanocubes, which can be attributed to their geometric and surface characteristics. The nanospheres, possessing a higher specific surface area, exhibited superior thermal conductivity, resulting in more effective heat dissipation. Conversely, the nanocubes, with their structured edges, induced localized turbulence, enhancing convective heat transfer, particularly at higher power inputs. This shape-dependent behavior highlights the necessity of selecting nanoparticle morphology based on specific application requirements. The findings suggest that nanosphere nanofluids are optimal for applications prioritizing maximum thermal efficiency, while nanocube nanofluids may be better suited for high-power applications where convective enhancement is beneficial.

Figure 5 illustrates the thermal efficiency of the heat pipe as a function of power input for DI water, nanosphere nanofluid, and nanocube nanofluid. The data reveal a significant efficiency boost with nanofluids. The DI water efficiency increases from 55 % at 40 kW to 65 % at 100 kW. The nanosphere nanofluid exhibits a peak efficiency of 72 % at 100 kW, while the nanocube nanofluid reaches 70 %. The 7-% higher efficiency of the nanosphere nanofluid compared to DI water demonstrates its superior ability to reduce thermal resistance. The difference between nanospheres and nanocubes, though marginal, highlights the role of shape-dependent heat transfer mechanisms.[17] The spherical shape ensures better thermal interaction due to isotropic heat conduction, while the cubic geometry generates localized turbulence, slightly offsetting its lower surface area.

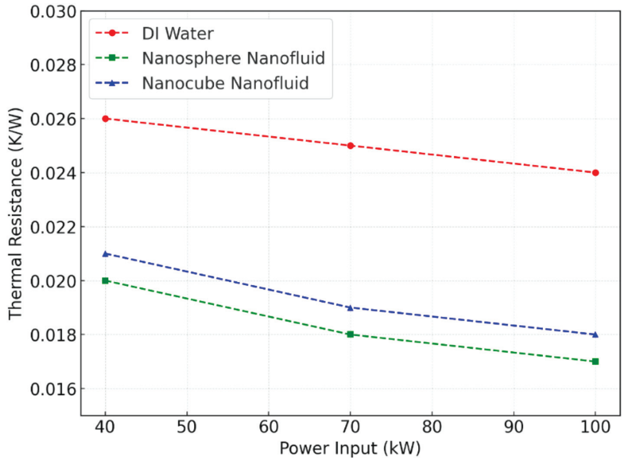

Figure 6: TR with power input

Figure 6 shows the thermal resistance of the heat pipe for DI water, nanosphere nanofluid, and nanocube nanofluid across varying power inputs. The results reveal a substantial reduction in thermal resistance with nanofluids. For DI water, thermal resistance decreases from 0.026 K/W at 40 kW to 0.024 K/W at 100 kW. In comparison, the nanosphere nanofluid exhibits a resistance as low as 0.017 K/W at 100 kW, indicating a 29-% improvement. The nanocube nanofluid achieves a thermal resistance of 0.018 K/W, reflecting a 25-% reduction.[18] These results align with the enhanced heat transfer coefficients observed. The lower resistance for nanospheres is consistent with their higher thermal conductivity and stability, while the reduction for nanocubes is largely attributed to their convective enhancements.[19]

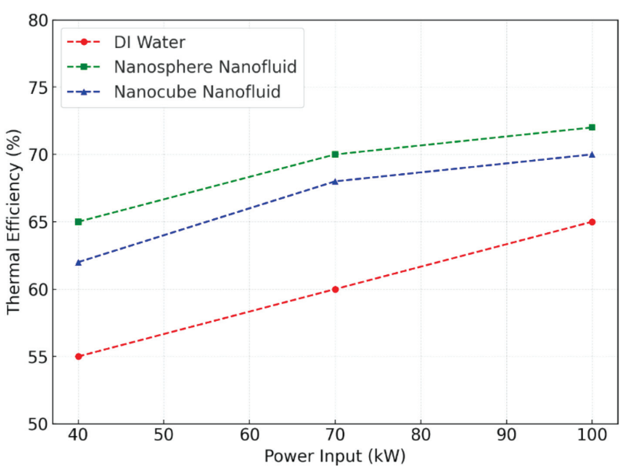

Figure 5: TE with power input

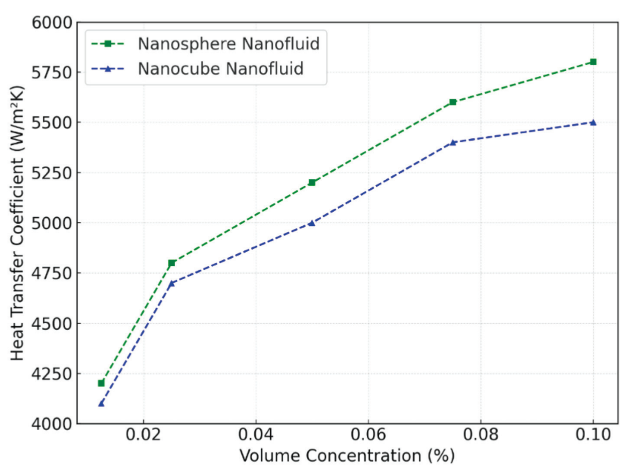

Figure 7: HTC with volume concentration

Figure 7 demonstrates the heat transfer coefficient as a function of volume concentration for nanosphere and nanocube nanofluids. Both nanoparticle morphologies show a significant increase in the HTC with increasing concentration. At 0.0125 % concentration, the HTC for nanospheres is 4200 W/m^{2}K, increasing to 5800 W/m^{2}K at 0.1 % concentration. Nanocubes follow a similar trend, with the HTC rising from 4100 W/m^{2}K to 5500 W/m^{2}K over the same concentration range. The higher HTC for nanospheres can be explained with their larger specific surface area and better dispersion stability.[20] At higher concentrations, nanocubes show improved performance due to enhanced convective effects resulting from their geometric shape. These results highlight the importance of optimizing nanoparticle concentration to maximize heat transfer performance.[21]

Figure 8 shows the thermal efficiency of the heat pipe as a function of volume concentration for nanosphere and nanocube nanofluids. Thermal efficiency increases steadily with concentration, with the nanosphere nanofluid achieving 72-% efficiency at 0.1-% concentration, compared to 70 % for nanocubes.[22] At a lower concentration (0.0125 %), nanospheres exhibit 60-% efficiency, whereas nanocubes show 58 %. This difference highlights the superior thermal properties of nanospheres at low concentrations. However, as the concentration increases, the convective enhancement of nanocubes becomes more prominent, narrowing the gap between the two morphologies. The results demonstrate that nanofluids significantly enhance the thermal performance and efficiency of heat pipes compared to DI water. The shape of nanoparticles plays a crucial role in determining the extent of these improvements. Nanospheres, with their higher specific surface area and uniform heat conduction, are more effective at lower concentrations. On the other hand, nanocubes, with their geometry-induced turbulence, become competitive at higher concentrations and power inputs.[23]

The optimization of nanofluid-based heat pipes using response surface methodology (RSM) provided valuable insights into the interplay between nanoparticle concentration, power input, and morphology, and their effects on key performance metrics such as heat transfer coefficient (HTC), thermal efficiency, and thermal resistance.

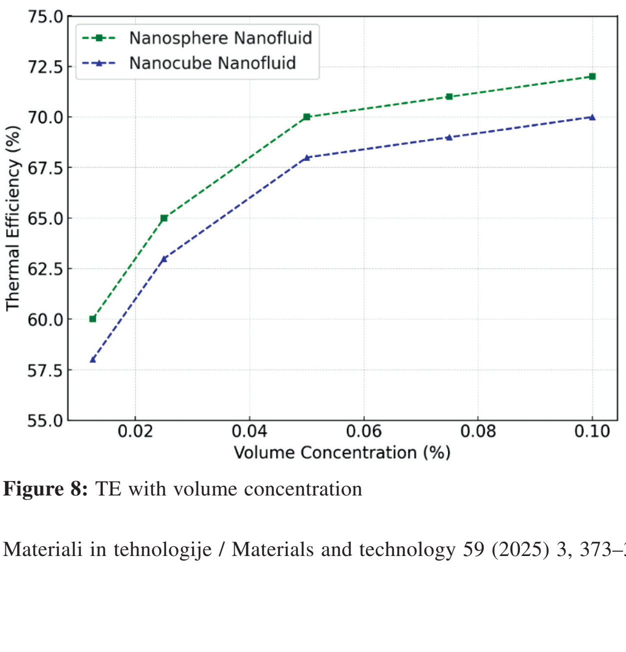

Figure 8: TE with volume concentration

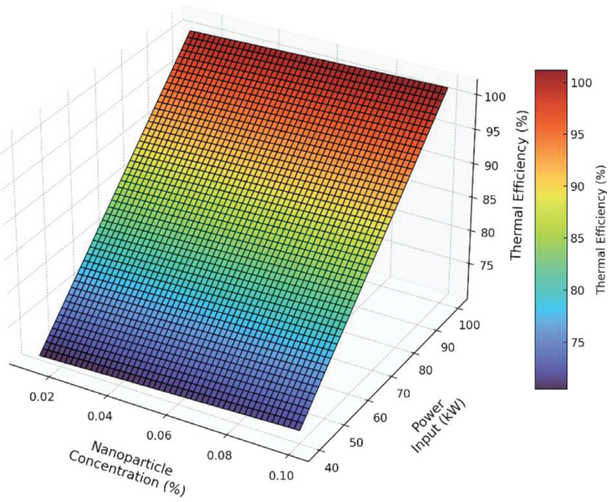

Figure 9: 3D surface plot for thermal efficiency

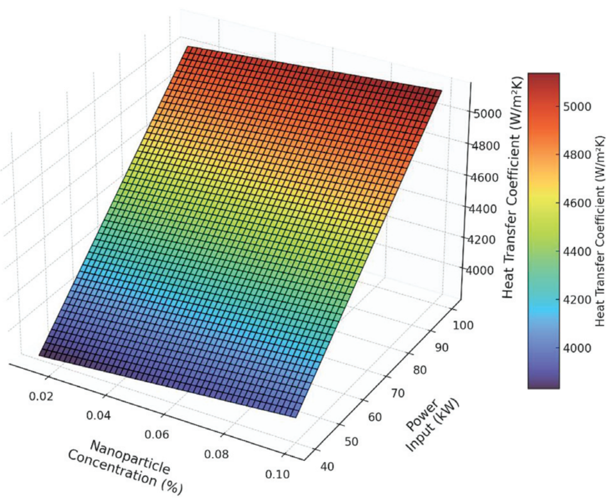

Figure 10: 3D surface plot for HTC

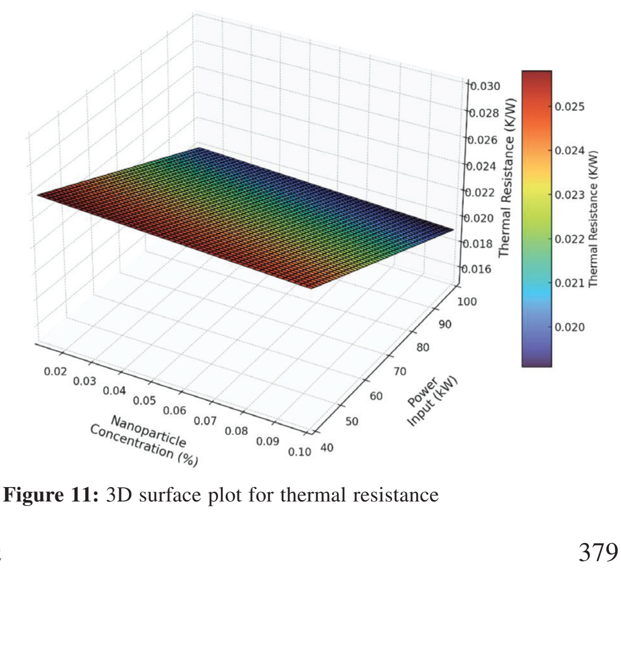

Figure 11: 3D surface plot for thermal resistance

RSM enabled the creation of a mathematical model that captured the complex relationships between these variables, allowing for precise tuning to achieve optimal performance. For the HTC, optimization revealed that increasing nanoparticle concentration and power input significantly enhanced performance, with nanospheres consistently outperforming nanocubes.[24] This superior performance of nanospheres is attributed to their higher specific surface area and isotropic thermal conduction, which promotes effective heat transfer. The optimal settings for the HTC were identified as a nanoparticle concentration of 0.1 %, power input of 100 kW, and nanosphere morphology, resulting in a predicted HTC of 5800 W/m^{2}K. This demonstrates the importance of leveraging both high thermal conductivity and stability in nanofluid applications.[25]

For thermal efficiency, the optimal nanoparticle concentration was slightly lower, 0.075 %, with a power input of 90 kW and a nanosphere morphology. The efficiency peaked at 72 %, highlighting that moderate concentrations and power inputs strike a balance between maximizing heat transfer and maintaining nanoparticle stability.[26] At higher concentrations, particle clustering and reduced dispersion stability diminished efficiency gains, underlining the need for optimized formulations for specific operating conditions. Thermal resistance, another critical response, was minimized at high nanoparticle concentrations and power inputs, with nanocubes demonstrating a slight advantage in this metric. The optimal settings were a concentration of 0.1 %, power input of 100 kW, and nanocube morphology, resulting in a predicted thermal resistance of 0.017 K/W. The geometric shape of nanocubes enhanced localized turbulence, compensating for their lower surface area compared to nanospheres.[27]

The response surfaces further reinforce these findings. The efficiency plot (**Figure 9**) revealed an optimal nanoparticle concentration of around 0.075 %, beyond which diminishing returns were observed due to particle agglomeration. For the HTC, the response surfaces showed a sharp increase with rising nanoparticle concentration and power input, while contour plots indicated that nanospheres maintained superior performance across the entire range of experimental conditions (**Figure 10**). For thermal resistance, the response surfaces highlighted the critical role of high power inputs in minimizing resistance, with nanocubes achieving comparable performance to nanospheres at these levels (**Figure 11**).

The study provided several key insights. Higher nanoparticle concentrations were shown to enhance HTC and reduce thermal resistance, while moderate concentrations were optimal for efficiency. Power input played a pivotal role, with higher levels maximizing HTC and minimizing resistance but potentially reducing efficiency due to excessive thermal gradients.[28] Morphology had a distinct influence, with nanospheres excelling in HTC and efficiency due to their uniform thermal conduction and stability, while nanocubes demonstrated better thermal resistance performance at high power inputs owing to their turbulence-inducing geometry.[29]

These findings have practical implications for advanced thermal management systems. Applications prioritizing heat transfer, such as electronics cooling, would benefit from nanosphere nanofluids, while systems requiring reduced thermal resistance, such as heat exchangers, could leverage nanocubes under high power conditions. The optimization through RSM provided a clear roadmap for enhancing heat pipe performance, demonstrating its efficacy as a decision-making tool in thermal engineering. This analysis underscores the potential of nanofluids to revolutionize thermal management by enabling highly efficient and customizable heat transfer solutions.[30] These findings provide a comprehensive understanding of how silver nanofluids enhance heat pipe performance. The shape-dependent effects and concentration-dependent trends offer valuable insights for optimizing nanofluid formulations for specific thermal management applications. Future studies could further explore the interaction between particle size, morphology, and base fluid properties to refine these results and expand their applicability to other heat transfer systems.

4 CONCLUSIONS

The experimental investigation of heat pipes using silver nanofluids with distinct nanoparticle morphologies, namely nanospheres and nanocubes, has provided significant insights into their thermal performance. The study demonstrated that nanosphere-based nanofluids consistently outperformed nanocube-based nanofluids in terms of the heat transfer coefficient and thermal efficiency, with the highest HTC of 5800 W/m^{2}K observed for nanospheres at the 0.1 % concentration and the 100 kW power input, representing a 38-% improvement over deionized water. In comparison, nanocubes achieved a maximum HTC of 5500 W/m^{2}K under the same conditions, showing a 31-% enhancement. Thermal efficiency followed a similar trend, peaking at 72 % for nanospheres and 70 % for nanocubes. The thermal resistance analysis revealed that nanospheres reduced resistance by up to 29 %, while nanocubes achieved a reduction of 25 % at the maximum power input and concentration level. These findings emphasize the importance of the nanoparticle shape in optimizing thermal properties, with nanospheres allowing superior performance due to their higher specific surface area and better dispersion stability, while nanocubes leveraged geometric-induced turbulence to enhance convective effects.

The study underscores the potential of silver nanofluids to improve the efficiency of heat pipe systems significantly. However, further research is recommended to explore the long-term stability of nanofluids, particularly under varying environmental conditions and extended operational periods. Additionally, investigating the interaction between nanoparticle size, morphology, and different base fluids would provide a deeper understanding of nanofluid behavior. Extending the analysis to other heat transfer systems, such as heat exchangers and cooling systems in electronics, could expand the applicability of these findings. Advanced modeling techniques, such as molecular dynamics simulations, could complement experimental results and optimize nanofluid formulations. These efforts would pave the way for innovative and efficient thermal management solutions across diverse industrial applications.

Conflict of interest statement

The author(s) declared no potential conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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