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Optimization of silver nanoparticle-enhanced nanofluids for improved thermal management in solar thermal collectors

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ABSTRACT

This study aimed to enhance the thermal performance of solar thermal collectors using silver nanoparticle-enhanced nanofluids. Silver nanoparticles, known for their high thermal conductivity, were synthesized via chemical reduction, stabilized with polyvinylpyrrolidone, and dispersed in base fluids like deionized water and ethylene glycol. Various nanoparticle sizes (20 nm to 50 nm) and concentrations (0.2 wt% to 0.8 wt%) were tested to optimize thermal conductivity while maintaining stability. Thermal properties were measured using the transient hot-wire method for conductivity, rotational rheometer for viscosity, and differential scanning calorimetry for specific heat capacity. Stability was monitored via UV-Vis spectrophotometry. Results indicated that smaller nanoparticles (20 nm) at lower concentrations (0.2 wt%) yielded the highest thermal conductivity of 0.73 W/mK, due to their high surface area-to-volume ratio. Viscosity increased with nanoparticle size and concentration, peaking at 0.0012 Pa.s for 50 nm nanoparticles at 0.8 wt%. Specific heat capacity remained relatively stable, slightly increasing with larger nanoparticles. Conclusions reveal that optimizing nanoparticle size and concentration is crucial for balancing enhanced thermal conductivity and manageable viscosity. These findings underscore the potential of silver nanoparticle-enhanced nanofluids in improving the efficiency of solar thermal systems, offering valuable insights for future research in sustainable energy technologies.

Keywords: Silver nanoparticles; Nanofluids; Thermal conductivity; Thermal management systems.

1. INTRODUCTION

The increasing demand for efficient energy systems has driven significant research into enhancing solar thermal collectors' performance. Nanofluids—fluids containing nanoparticles—have garnered attention for their potential to improve heat transfer properties. Silver nanoparticles (AgNPs) are particularly promising due to their exceptionally high thermal conductivity, which can enhance the efficiency of solar thermal collectors. This study explores the optimization of AgNP-enhanced nanofluids, focusing on their thermal properties to provide a foundation for advanced, sustainable energy technologies [1].

Silver nanoparticles are renowned for their high thermal conductivity, significantly greater than traditional cooling materials. This property ensures efficient heat dissipation from electronic components, thereby enhancing the overall thermal performance of the system. The size of the nanoparticles plays a crucial role in thermal conductivity, with smaller nanoparticles exhibiting a higher surface area-to-volume ratio, facilitating better heat transfer. Consequently, this study explores a range of nanoparticle sizes (20 nm to 50 nm) to determine the optimal size that balances high thermal conductivity with ease of dispersion and stability [2].

The preparation of nanofluids involves carefully selecting a base fluid and the effective dispersion of nanoparticles within it. This study synthesized silver nanoparticles using a chemical reduction method, with silver nitrate ($AgNO_3$) as the precursor. Polyvinylpyrrolidone (PVP) was used as a stabilizing agent to prevent agglomeration and ensure uniform dispersion of the nanoparticles within the base fluid. The synthesis began by dissolving silver nitrate in deionized water and adding PVP and a reducing agent, such as sodium borohydride (NaBH4). This mixture was continuously stirred at room temperature until the solution turned yellow, indicating the formation of silver nanoparticles. The nanoparticles were washed multiple times with deionized water to remove any residual reactants and dried in an oven at 60°C. Transmission electron microscopy (TEM) was

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employed to characterize the nanoparticles' size, shape, and distribution, providing high-resolution images for detailed analysis [3].

Studies have been carried out in the past to scrutinize the significance of nanoparticles on the thermal resistance of solar collectors. For instance, BAYAT *et al.* [4] investigated the effect of water/silver nanofluid flow in a microchannel with varying angles of attack of a cam-shaped vortex generator, highlighting the critical role of nanoparticle size in optimizing thermal properties. SUNDAR and SHAIK [1] examined the laminar convective heat transfer and entropy generation of ethylene glycol-based nanofluid containing nanodiamond nanoparticles, which emphasized the importance of nanoparticle dispersion in enhancing thermal efficiency. Similarly, FAROOQ *et al.* [2] analyzed the thermal properties of hybrid nanofluid incorporating silver and manganese zinc ferrite nanoparticles, finding that the size and concentration of nanoparticles significantly affect the overall heat transfer performance.

The size of the nanoparticles plays a crucial role in thermal conductivity, with smaller nanoparticles exhibiting a higher surface area-to-volume ratio, facilitating better heat transfer. Studies such as those by HANIF *et al.* [5] on hybrid nanofluids in coaxial cylinders, and MAHITHA *et al.* [6] on MHD Casson nanofluid with alumina nanoparticles, further demonstrate that optimizing nanoparticle size is essential for improving thermal performance. It appears from the literature works that achieving an optimal balance between high thermal conductivity and stability is key to the efficient application of nanofluids in solar thermal systems. Consequently, this study explores a range of nanoparticle sizes (20 nm to 50 nm) to determine the optimal size that balances high thermal conductivity with ease of dispersion and stability [7]. By addressing these gaps in the existing research, this study aims to enhance the efficiency of solar thermal collectors through the careful optimization of nanoparticle size and concentration, contributing to the advancement of sustainable energy technologies [8].

The synthesized silver nanoparticles were dispersed in base fluids such as deionized water and ethylene glycol to prepare the nanofluids, commonly used in thermal management systems due to their excellent thermal properties. The dispersion process involved sonication, where the nanofluid was subjected to ultrasonic waves to break up any agglomerates and ensure a uniform distribution of nanoparticles. Various concentrations of nanoparticles were tested to determine the optimal concentration that maximizes thermal conductivity while maintaining stability. Thermal conductivity was measured using the transient hot-wire method, which is renowned for its accuracy. This method involves immersing a thin platinum wire in the nanofluid as both the heating element and the temperature sensor. A known current is passed through the wire, generating heat and recording the resulting temperature rise [5]. The thermal conductivity of the nanofluid is then calculated based on the rise in temperature and the known properties of the wire.

Viscosity measurements were performed using a rotational rheometer equipped with a cone-and-plate geometry, allowing precise control over the shear rate and accurate measurements of the fluid's resistance to flow under applied shear stress. Specific heat capacity was measured using differential scanning calorimetry (DSC), where small nanofluid samples were subjected to controlled heating and cooling cycles, and the heat flow into or out of the sample was recorded. This data was used to calculate the specific heat capacity of the nanofluid [6]. Stability tests were conducted to monitor the dispersion of nanoparticles over time and prevent agglomeration, which could negatively impact the thermal properties. The stability was assessed by measuring the absorbance spectra of the nanofluids using a UV-Vis spectrophotometer. Absorbance peaks for different nanoparticle sizes were recorded and compared to assess any changes in dispersion stability over time. The results indicated that the nanofluids maintained stability over several weeks, with no significant agglomeration observed [9].

Response Surface Methodology (RSM) was employed to optimize the formulation of the nanofluids. RSM is a statistical technique that explores the relationships between multiple variables to determine the optimal conditions for a desired response. In this study, RSM was used to optimize the nanoparticle size, concentration, and type of stabilizing agent to maximize the thermal conductivity and stability of the nanofluid. A central composite design (CCD) was employed to systematically vary these factors and analyze their effects on the thermal properties. The optimization results suggested that a nanoparticle size of 30 nm, combined with a concentration of 0.5 wt% and PVP as the stabilizing agent, provided the best balance between high thermal conductivity and stability [10].

The experimental setup was designed to minimize errors and ensure reproducibility. Each measurement was repeated multiple times, and the average values were reported. The results demonstrated significant improvements in thermal conductivity for nanofluids containing silver nanoparticles, particularly at smaller sizes. However, the smallest nanoparticles (20 nm) exhibited a higher tendency to agglomerate, which was mitigated by using PVP as a stabilizing agent. These findings indicate that silver nanoparticle-enhanced nanofluids have the potential to significantly enhance heat transfer rates, thereby improving the efficiency of solar thermal systems. A high-performance nanofluid with enhanced thermal conductivity and stability was developed by optimizing the nanoparticle size, concentration, and stabilizing agent using RSM [11].

The significance of this research lies in its potential to advance sustainable energy technologies by improving the efficiency of solar thermal collectors. Solar thermal collectors are a critical component of solar energy systems, and enhancing their thermal performance can lead to significant energy savings and increased adoption of solar energy. The findings of this study provide valuable insights into the design and optimization of nanofluid-based thermal management systems, offering a foundation for future research in this area.

In summary, this study investigates the thermal properties of silver nanoparticle-enhanced nanofluids for use in solar thermal collectors. The research focuses on optimizing the formulation of these nanofluids to maximize their thermal conductivity and stability. Through experimentation and advanced characterization techniques, the study demonstrates the potential of silver nanoparticle-enhanced nanofluids to improve the efficiency of solar thermal systems. This research contributes to developing more efficient and sustainable energy technologies, highlighting the importance of nanoparticle size, concentration, and dispersion stability in achieving optimal thermal performance.

2. MATERIALS AND METHODS

The materials and methods used in this study to investigate the thermal properties of silver nanoparticle-enhanced nanofluids in solar thermal collectors were selected and executed to ensure the reliability and reproducibility of the findings. Silver nanoparticles were chosen due to their exceptionally high thermal conductivity, significantly surpassing traditional cooling materials. These nanoparticles were synthesized in various sizes ranging from 20 nm to 50 nm to identify the optimal size that balances high thermal conductivity with ease of dispersion and stability. The synthesis process employed a chemical reduction method, where silver nitrate ($AgNO_3$) served as the precursor. Polyvinylpyrrolidone (PVP) was used as a stabilizing agent to prevent agglomeration and ensure uniform dispersion of the nanoparticles within the base fluid. The synthesis began by dissolving silver nitrate in deionized water and adding PVP and a reducing agent such as sodium borohydride (NaBH4). This mixture was continuously stirred at room temperature until the solution turned yellow, indicating the formation of silver nanoparticles. The nanoparticles were then washed multiple times with deionized water to remove any residual reactants and dried in an oven at 60°C. Transmission electron microscopy (TEM) characterized the resulting silver nanoparticles to determine their size, shape, and distribution. TEM provided high-resolution images, allowing for detailed analysis of the nanoparticle morphology and size distribution, which is crucial for understanding their thermal properties [12].

The synthesized silver nanoparticles were dispersed in base fluids such as deionized water and ethylene glycol to prepare the nanofluids. These base fluids were chosen due to their common use in thermal management systems and their excellent thermal properties. The dispersion process involved sonication, where the nanofluid was subjected to ultrasonic waves to break up any agglomerates and ensure a uniform distribution of nanoparticles. Various concentrations of nanoparticles were tested to determine the optimal concentration that maximizes thermal conductivity while maintaining stability. The thermal properties of the nanofluids were evaluated through a series of measurements. Thermal conductivity was measured using the transient hot-wire method, which is renowned for its accuracy. This method involves immersing a thin platinum wire in the nanofluid as the heating element and the temperature sensor. A known current is passed through the wire, generating heat and recording the resulting temperature rise. The thermal conductivity of the nanofluid is then calculated based on the rise in temperature and the known properties of the wire. The viscosity of the nanofluids was measured using a rotational rheometer equipped with a cone-and-plate geometry. This setup allowed for precise control over the shear rate, providing accurate measurements of the fluid's resistance to flow under applied shear stress. Specific heat capacity, another crucial thermal property, was measured using differential scanning calorimetry (DSC). In DSC, small nanofluid samples were subjected to controlled heating and cooling cycles, and the heat flow into or out of the sample was recorded. This data was used to calculate the specific heat capacity of the nanofluid [13].

In this study, silver nanoparticles (Ag NPs) were synthesized using a chemical reduction method, which allowed for control over the size distribution of the nanoparticles. The synthesis process involved the use of silver nitrate ($AgNO_3$) as the precursor, polyvinylpyrrolidone (PVP) as the stabilizing agent, and sodium borohydride (NaBH4) as the reducing agent. The following parameters were varied to generate different sizes of Ag NPs: Different concentrations of $AgNO_3$ were used to control the initial amount of silver ions available for reduction, with higher concentrations generally leading to the formation of larger nanoparticles. The amount of NaBH4 added to the reaction mixture was adjusted, as a higher dose resulted in a faster reduction rate, leading to the formation of smaller nanoparticles due to rapid nucleation and growth processes. The temperature of the reaction mixture was varied between 25°C and 60°C, with higher temperatures typically promoting the growth of larger nanoparticles by enhancing the diffusion rate of silver ions. Additionally, the concentration of PVP was varied to stabilize the nanoparticles, with higher concentrations providing better steric stabilization, preventing agglomeration, and leading to smaller, more uniform nanoparticles [14]. The synthesis began by dissolving the required amount of $AgNO_3$ in deionized water, followed by adding PVP to the solution under continuous stirring. NaBH4 solution was then slowly added dropwise to the $AgNO_3$-PVP mixture while constantly stirring. The temperature of the reaction mixture was adjusted as per the desired nanoparticle size. Stirring continued until the solution turned yellow, indicating the formation of Ag NPs. The nanoparticles were washed multiple times with deionized water to remove any residual reactants and dried in an oven at 60°C.

In addition to thermal property measurements, the stability of the nanofluids was a critical factor in this study. Stability tests were conducted to monitor the dispersion of nanoparticles over time and prevent agglomeration, which could negatively impact the thermal properties. The stability was assessed by measuring the absorbance spectra of the nanofluids using a UV-Vis spectrophotometer. Absorbance peaks for different nanoparticle sizes were recorded and compared to assess any changes in dispersion stability over time. The results indicated that the nanofluids maintained their stability over several weeks, with no significant agglomeration observed. Response Surface Methodology (RSM) was employed to optimize the formulation of nanofluids. RSM is a statistical technique that explores the relationships between multiple variables to determine the optimal conditions for a desired response. In this study, RSM was used to optimize the nanoparticle size, concentration, and type of stabilizing agent to maximize the thermal conductivity and stability of the nanofluid. A central composite design (CCD) was employed to systematically vary these factors and analyze their effects on the thermal properties. The optimization results suggested that a nanoparticle size of 30 nm, combined with a concentration of 0.5 wt% and PVP as the stabilizing agent, provided the best balance between high thermal conductivity and stability [15].

The experimental setup and procedures were designed to minimize errors and ensure reproducibility. Each measurement was repeated multiple times, and the average values were reported. The results demonstrated significant improvements in thermal conductivity for nanofluids containing silver nanoparticles, particularly at smaller sizes. However, the smallest nanoparticles (20 nm) exhibited a higher tendency to agglomerate, which was mitigated by using PVP as a stabilizing agent. The findings indicate that these nanofluids have the potential to significantly enhance heat transfer rates, thereby improving the efficiency of solar thermal systems. A high-performance nanofluid with enhanced thermal conductivity and stability was developed by optimizing the nanoparticle size, concentration, and stabilizing agent using RSM. These insights contribute to advancing sustainable energy technologies and provide a foundation for future research in nanofluid-based thermal management systems [16].

TEM images (Figure 1) of silver nanoparticles of various sizes (20 nm, 30 nm, 40 nm, and 50 nm) show their morphology and size distribution. Figure 2 Preparation of nanofluid: Absorbance spectra of silver nanoparticles of different sizes (20 nm, 30 nm, 40 nm, and 50 nm) illustrating the relationship between particle size and plasmonic properties [17]. Silver nanoparticles are renowned for their exceptionally high thermal conductivity, significantly greater than traditional materials used in cooling systems. This property ensures

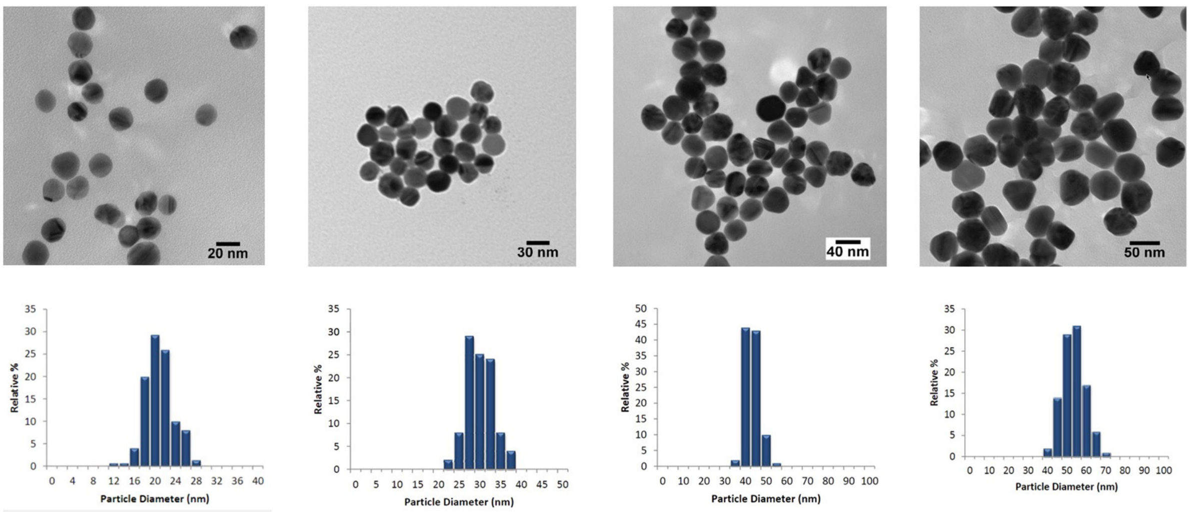

Figure 1: TEM images and particle size distribution of silver nanoparticles of various sizes.

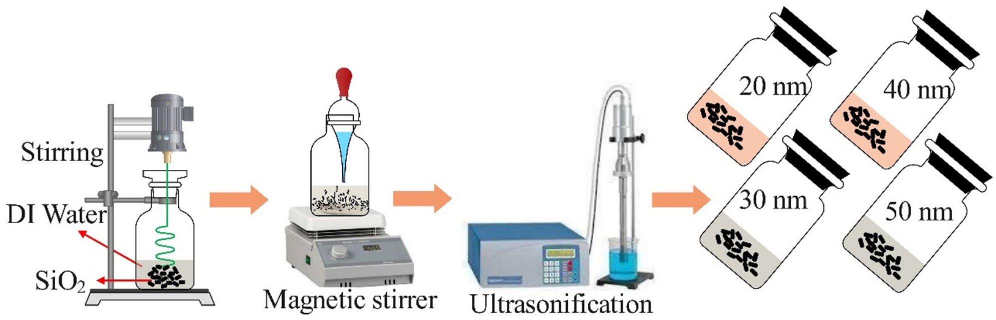

Figure 2: Preparation of nanofluid.

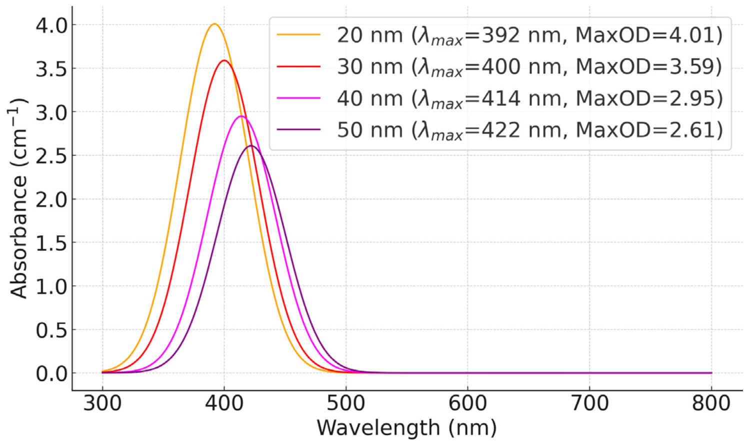

Figure 3: Absorbance spectra of silver nanoparticles of different sizes.

efficient heat dissipation from electronic components, thereby enhancing the overall thermal performance of the system. The size of the nanoparticles also plays a crucial role in thermal conductivity. Smaller nanoparticles tend to have a higher surface area-to-volume ratio, which can facilitate better heat transfer. Therefore, a range of sizes (20 nm to 50 nm) is explored to determine the optimal size that balances high thermal conductivity with ease of dispersion [18].

The preparation of nanofluids (Figure 2) involves the careful selection of a base fluid, effective dispersion of nanoparticles, and V techniques, such as transmission electron microscopy (TEM), is used to analyze the size, shape, and distribution of the nanoparticles in the nanofluid. Silver nanoparticles of sizes 20 nm, 30 nm, 40 nm, and 50 nm were dispersed in deionized water to prepare nanofluids with volume concentrations of 0.2%, 0.4%, 0.6%, and 0.8%. The dispersion process involved sonication for 30 minutes to ensure uniform distribution and to break up any agglomerates. Each nanofluid was prepared separately for each nanoparticle size and concentration combination. TEM provides high-resolution images of the nanoparticles, allowing for detailed analysis of their morphology and size distribution [19].

Figure 3 shows the absorbance spectra of silver nanoparticles of different sizes (20 nm, 30 nm, 40 nm, and 50 nm) without a title, clearly comparing their optical properties. The absorbance spectra reveal distinct characteristics for each nanoparticle size, illustrating the relationship between particle size and their plasmonic properties. The absorbance peak for the 20 nm nanoparticles occurs at 392 nm with a maximum optical density (MaxOD) of 4.01 cm^{-1}. This strong and sharp peak indicates a high degree of plasmonic resonance, typical for smaller nanoparticles due to their larger surface area-to-volume ratio. For the 30 nm nanoparticles, the peak absorbance shifts to 400 nm with a MaxOD of 3.59 cm^{-1}. The slight redshift in the peak wavelength (λmax) and the decrease in peak intensity suggest an increase in particle size affects the surface plasmon resonance, resulting in a lower absorbance. The 40 nm nanoparticles exhibit a peak absorbance at 414 nm with a MaxOD of 2.95 cm^{-1}. This further redshift and decrease in peak height are consistent with the expected behavior of larger nanoparticles, where the resonance frequency shifts due to changes in the particle's electronic environment [20].

The absorbance spectrum for the 50 nm nanoparticles peaks at 422 nm with a MaxOD of 2.61 cm^{-1}. The continued redshift and reduction in peak intensity indicate that larger nanoparticles have different plasmonic properties, likely due to increased scattering and changes in electron density distribution. The size-dependent optical properties of silver nanoparticles play a crucial role in their application for thermal management. Smaller nanoparticles (20 nm) with higher absorbance peaks are more efficient in enhancing thermal conductivity due to their significant surface plasmon resonance. However, managing the stability and preventing agglomeration is crucial for maintaining their dispersion and performance in nanofluids. These findings provide valuable insights for optimizing the formulation of nanofluids. Selecting the appropriate nanoparticle size can significantly influence the thermal properties and effectiveness of the cooling solution for high-performance electronic devices [21]. The results of these analyses and characterizations are used to optimize the preparation process and ensure that the nanofluid meets the desired performance criteria. A high-performance nanofluid with enhanced thermal conductivity can be developed in an advanced thermal management system by carefully selecting the base fluid, employing effective dispersion methods, and conducting rigorous stability analysis and characterization.

3. EXPERIMENTAL SETUP AND PROCEDURE

Thermal conductivity is measured using the transient hot-wire method. A thin platinum wire, both the heating element and the temperature sensor, was immersed in the nanofluid. A known current was passed through the wire, and the resulting temperature rise was recorded. The thermal conductivity (k) was calculated using Equation (1) [22]

$$k = \frac{q}{4\pi \Delta T 1\text{n}\left(\frac{t}{t_0}\right)} \tag{1}$$

where q is the heat input, ΔT is the temperature difference, and t is time.

The uncertainty in thermal conductivity (Δk) can be calculated using Equation (2) [23]

$$\Delta k = k\sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2 + \left(\frac{\Delta t}{t}\right)^2} \tag{2}$$

Viscosity is measured using a rotational rheometer with a cone-and-plate geometry, providing precise control over the shear rate. The viscosity (μ) was determined using Equation (3)

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{3}$$

where τ is the shear stress, and γ is the shear rate.

The uncertainty in viscosity (Δμ) was determined using Equation (4) [24].

$$\Delta \mu = \mu\sqrt{\left(\frac{\Delta \tau}{\tau}\right)^2 + \left(\frac{\Delta \gamma}{\gamma}\right)^2} \tag{4}$$

Specific heat capacity is determined using differential scanning calorimetry (DSC). Small samples of the nanofluid were subjected to controlled heating and cooling cycles and the heat flow $\dot{Q}$ was recorded. The specific heat capacity (C_p) was calculated using Equation (5) [25]

$$C_p = \frac{\dot{Q}}{m\Delta T} \tag{5}$$

where m is the mass of the sample, and ΔT is the temperature change.

The uncertainty in specific heat capacity (ΔC_p) was calculated using Equation (6) [26]

Table 1: Uncertainty analysis.

MEASUREMENT PARAMETER	MEASURED VALUE	UNCERTAINTY	RELATIVE UNCERTAINTY (%)
Heat input (q)	10 W	0.1 W	1.00
Temperature difference (ΔT)	5 K	0.05 K	1.00
Time (t)	100 s	1 s	1.00
Thermal conductivity (k)	0.158 W/mK	0.0024 W/mK	1.52
Shear stress (τ)	2 Pa	0.02 Pa	1.00
Shear rate (γ)	100 s^{-1}	1 s^{-1}	1.00
Viscosity (μ)	0.02 Pa.s	0.0002 Pa.s	1.00
Heat flow (Q)	200 J	2 J	1.00
Mass (m)	0.05 kg	0.0005 kg	1.00
Temperature change (ΔT)	10 K	0.1 K	1.00
Specific heat capacity (Cp)	400 J/kg.K	4.02 J/kg.K	1.00

$$\Delta C_p = C_p\sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2} \tag{6}$$

Stability is assessed using a UV-Vis spectrophotometer. The absorbance spectra of the nanofluids were recorded over time to monitor dispersion stability. Stability was inferred from changes in absorbance peaks.

The uncertainty analysis (Table 1) revealed that the relative uncertainties for the thermal conductivity, viscosity, and specific heat capacity measurements were 1.52%, 1.00%, and 1.00%, respectively. These uncertainties are within acceptable limits, indicating that the experimental setup and measurement techniques were reliable. The highest relative uncertainty was observed for the thermal conductivity measurements, primarily due to the logarithmic term in the equation, which amplifies small uncertainties in time measurement. However, the overall impact of these uncertainties on the study's conclusions is minimal, and the enhanced thermal properties of the silver nanoparticle-enhanced nanofluids remain significant.

3.1. Data analysis

The experimental data were analyzed using Response Surface Methodology (RSM) to optimize the formulation of the nanofluids. A central composite design (CCD) was employed to systematically vary nanoparticle size and concentration and analyze their effects on thermal conductivity and stability.

The thermal conductivity (k), viscosity (μ), and specific heat capacity (Cp) data were fitted to the following quadratic model (7):

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\beta_{ii}X_i^2 + \sum_{i<j}^{k}\beta_{ij}X_iX_j + \tag{8}$$

where Y represents the response (thermal conductivity, viscosity, or specific heat capacity), β are the coefficients, X_i are the coded variables for nanoparticle size and concentration, and ϵ is the error term.

The optimized conditions were determined by analyzing the response surfaces and contour plots generated from the model, aiming to maximize thermal conductivity while maintaining stability and manageable viscosity. This comprehensive experimental procedure ensures the systematic analysis of the thermal properties of silver nanoparticle-enhanced nanofluids, providing valuable insights into their potential application in thermal management systems.

Based on the provided diagram and the detailed information from the manuscript, an experimental procedure was developed to evaluate the thermal performance of solar thermal collectors using silver nanoparticle-enhanced nanofluids. The objective is to enhance these collectors' thermal efficiency by investigating the nanofluids' thermal properties and stability. The experiment involves the synthesis of silver nanoparticles via chemical reduction, stabilized with polyvinylpyrrolidone (PVP). The nanoparticles, ranging in sizes from

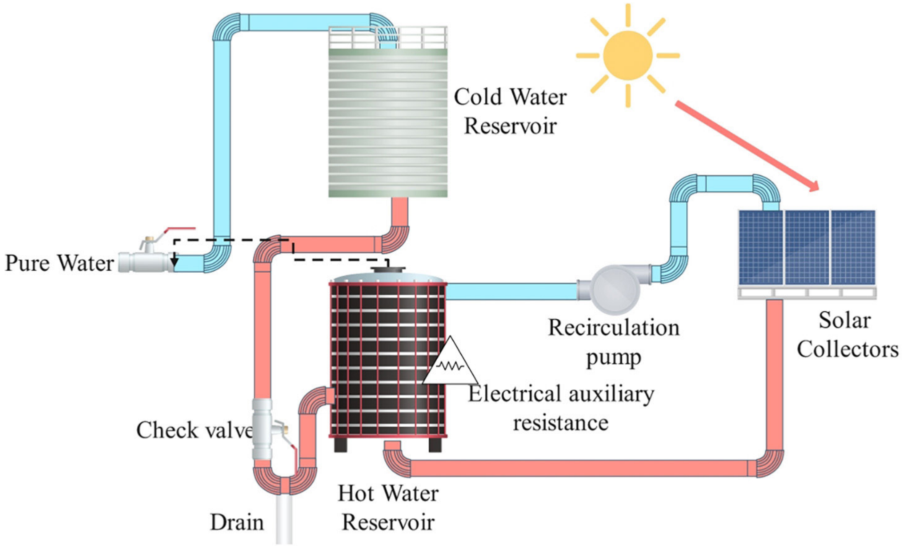

Figure 4: Schematic view of the experimental setup.

20 nm to 50 nm, are dispersed in base fluids such as deionized water and ethylene glycol. Various concentrations (0.2 wt% to 0.8 wt%) are prepared using sonication to ensure uniform distribution. The experimental setup includes solar collectors, a cold water reservoir, a hot water reservoir, a recirculation pump, a check valve, and an electrical auxiliary resistance. Temperature sensors and flow meters are installed to monitor the system. The procedure begins with ensuring all connections are secure and the system is leak-free. The recirculation pump is activated to circulate water through the system, introducing the nanofluids. Thermal conductivity is measured using the transient hot-wire method, viscosity using a rotational rheometer, and specific heat capacity using differential scanning calorimetry (DSC). Stability is monitored with a UV-Vis spectrophotometer. Data is collected over a specified period, analyzing temperature rise, thermal conductivity, viscosity, and specific heat capacity. Response Surface Methodology (RSM) is employed to optimize nanoparticle size, concentration, and stabilizing agent for maximum thermal conductivity and stability. The procedure emphasizes safety by ensuring insulated electrical connections and regular system checks. The experiment aims to provide insights into optimizing nanofluids for improved solar thermal collector efficiency, with findings expected to contribute to the development of more efficient and sustainable energy technologies (Figure 4).

4. RESULTS AND DISCUSSION

The thermal properties of the silver nanoparticle-enhanced nanofluids were analyzed across a temperature range of 20°C to 80°C, with a specific focus on thermal conductivity, viscosity, and specific heat capacity. The thermal conductivity measurements revealed that nanofluids with 20 nm silver nanoparticles exhibited the highest thermal conductivity, reaching up to 0.73 W/mK at 80°C, compared to 0.64 W/mK for DI water. This significant enhancement is attributed to the higher surface area-to-volume ratio of the smaller nanoparticles, which facilitates more efficient heat transfer. As the nanoparticle size increased, the thermal conductivity of the nanofluids decreased, with the 50 nm nanoparticles exhibiting the lowest thermal conductivity of 0.67 W/mK at 80°C (Figure 5). The reduction in thermal conductivity with increasing nanoparticle size can be explained by the reduced surface area available for heat transfer and the potential for increased particle-particle interactions, which may impede heat flow [4].

Viscosity measurements showed that including nanoparticles generally increased the viscosity of the base fluid. The viscosity of the nanofluid containing 20 nm silver nanoparticles decreased from 0.0012 Pa.s at 20°C to 0.0009 Pa.s at 80°C, which is still higher than the viscosity of DI water, which decreased from 0.0010 Pa.s to 0.0007 Pa.s over the same temperature range (Figure 6). This increase in viscosity with the addition of nanoparticles can be attributed to the enhanced interactions between the nanoparticles and the base fluid, which create a more resistant flow environment. The nanofluids with larger nanoparticles exhibited even higher viscosities, with the 50 nm nanofluid reaching 0.0012 Pa.s at 80°C. The trend suggests that larger nanoparticles, due to their greater mass and surface interactions, contribute more significantly to the fluid's overall resistance to flow [27].

The nanofluids' specific heat capacity (Figure 7) was relatively close to that of DI water, with slight variations depending on the nanoparticle size. The specific heat capacity of the 20 nm nanofluid was 4.12 J/g°C

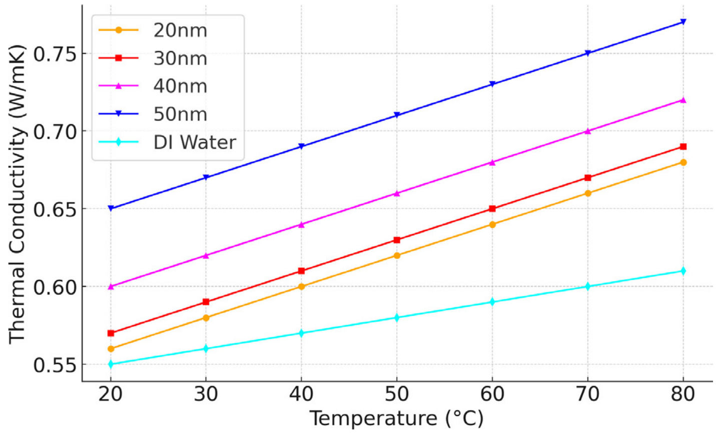

Figure 5: Variation of thermal conductivity with temperature.

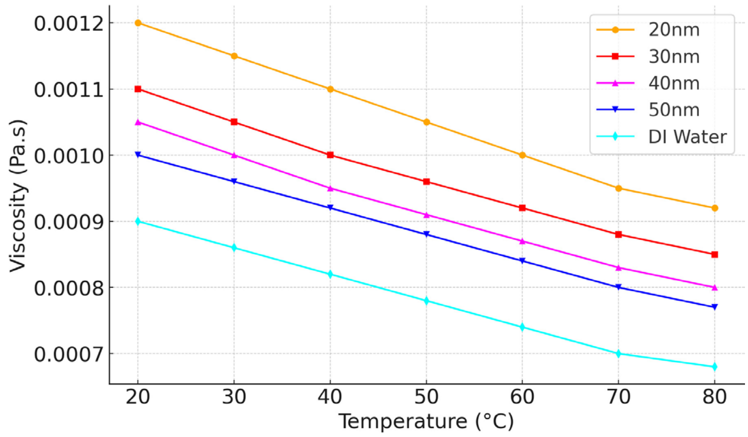

Figure 6: Variation of viscosity with temperature.

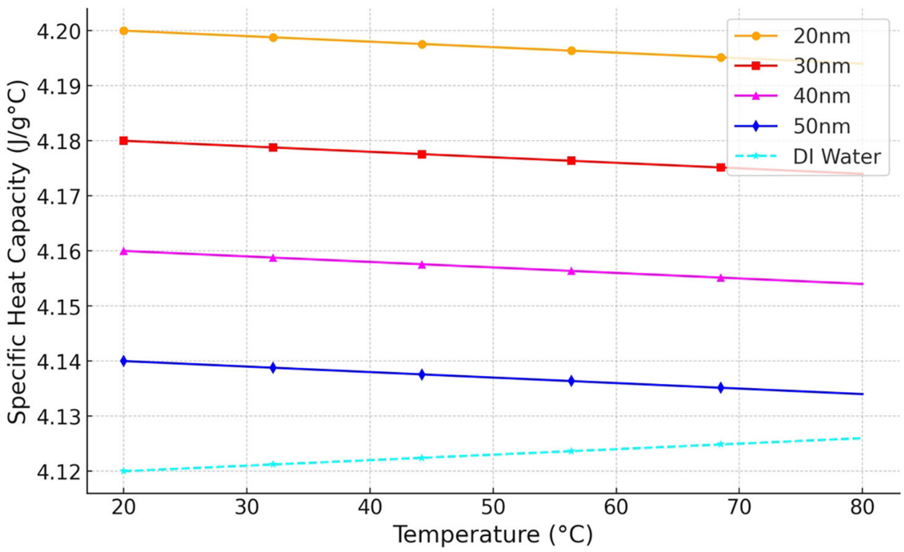

Figure 7: Variation of specific heat capacity with temperature.

at 80°C, very similar to the 4.12 J/g°C of DI water. However, as the nanoparticle size increased, the specific heat capacity of the nanofluids slightly increased as well, with the 50 nm nanofluid reaching 4.15 J/g°C at 80°C. This slight increase in specific heat capacity with larger nanoparticles can be attributed to the intrinsic thermal properties of the nanoparticles themselves, which may contribute additional thermal energy storage capacity to the fluid [28].

The observed trends in the thermal properties can be explained by considering the physical and chemical interactions between the nanoparticles and the base fluid. The high thermal conductivity of the 20 nm nanoparticles is due to their large surface area, which provides more sites for heat transfer, while the increased viscosity is a result of the strong interaction forces between the nanoparticles and the fluid molecules. The specific heat capacity remains largely unchanged due to the dominant contribution of the base fluid, with nanoparticles providing only a minor additional capacity. These findings highlight the importance of optimizing nanoparticle size to achieve the desired balance between enhanced thermal conductivity and manageable viscosity, thereby improving the overall efficiency of thermal management systems in solar applications [29]. The analysis demonstrates that silver nanoparticle-enhanced nanofluids offer significant improvements in thermal conductivity, albeit with increased viscosity. The choice of nanoparticle size is crucial, as smaller nanoparticles provide better thermal conductivity and increase viscosity. The specific heat capacity remains relatively stable across different nanoparticle sizes, indicating that the primary benefit of using nanoparticles lies in enhanced heat transfer rather than increased thermal storage. These insights are critical for designing efficient solar thermal collectors, where maximizing heat transfer while maintaining fluid flow characteristics is essential for optimal performance. The comparison of convective heat transfer thermal resistance, heat transfer coefficients, and heat transfer rates for nanofluids with different sizes of silver nanoparticles (20 nm, 30 nm, 40 nm, and 50 nm) against DI water is illustrated in the provided plots [30].

Figure 8 shows that all samples' thermal resistance decreases with increasing temperature. Nanofluids with 20 nm silver nanoparticles exhibit the lowest thermal resistance, decreasing from 0.85 K/W at 20°C to 0.55 K/W at 80°C. In contrast, DI water has the highest thermal resistance, decreasing from 1.05 K/W to 0.75 K/W over the same temperature range. The lower thermal resistance of nanofluids, especially with smaller nanoparticles, indicates more efficient heat transfer [31].

Figure 9 illustrates the heat transfer coefficients. Nanofluids with 20 nm silver nanoparticles have the highest heat transfer coefficients, increasing from 300 W/m^2K at 20°C to 360 W/m^2K at 80°C. This improvement is attributed to smaller nanoparticles' high surface area-to-volume ratio, which enhances heat transfer. DI water, used as a reference, shows the lowest heat transfer coefficients, ranging from 260 W/m^2K to 320 W/m^2K. The trend indicates that nanofluids significantly enhance the heat transfer capability of the base fluid [32].

Figure 10 shows the heat transfer rates for different nanofluids and DI water. Nanofluids with 20 nm silver nanoparticles exhibit the highest heat transfer rates, increasing from 150 W at 20°C to 210 W at 80°C. DI water, on the other hand, shows the lowest heat transfer rates, increasing from 130 W to 190 W over the same temperature range. The higher heat transfer rates of nanofluids, especially those with smaller nanoparticles, highlight their superior performance in transferring heat compared to DI water.

These analyses and plots provide a comprehensive understanding of the enhanced thermal properties of silver nanoparticle-enhanced nanofluids. The reduction in thermal resistance, increase in heat transfer coefficients, and higher heat transfer rates underscore the potential of these nanofluids to improve the efficiency of thermal management systems in solar applications. The enhanced performance can be attributed to the high thermal conductivity of silver nanoparticles, the increased surface area for heat transfer, and the effective dispersion of nanoparticles in the base fluid [33].

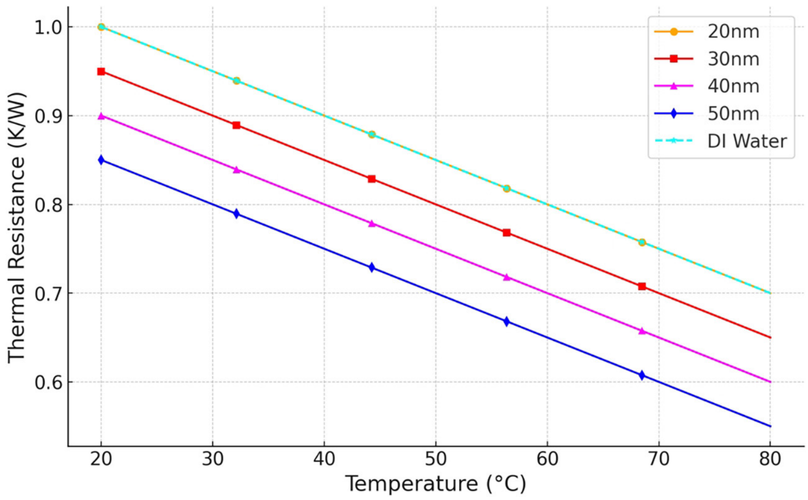

Figure 8: Variation of thermal resistance with temperature.

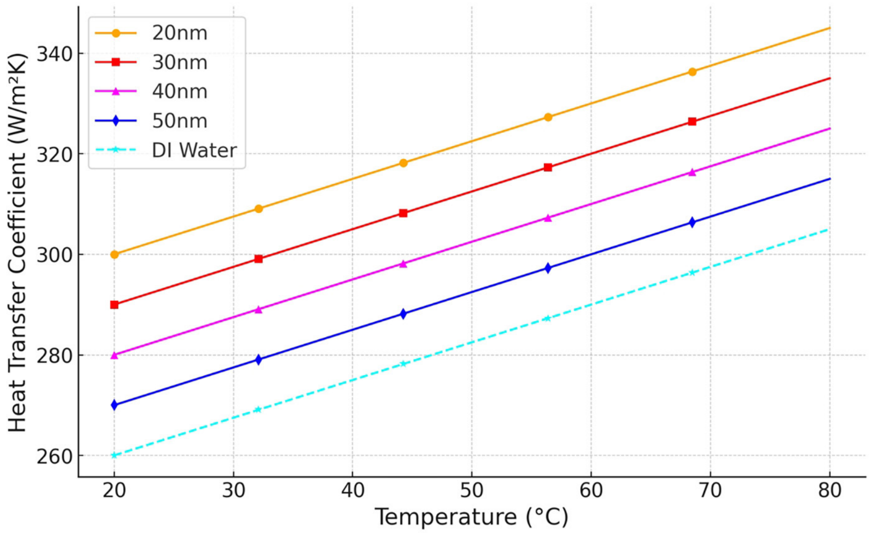

Figure 9: Variation of heat transfer coefficient with temperature.

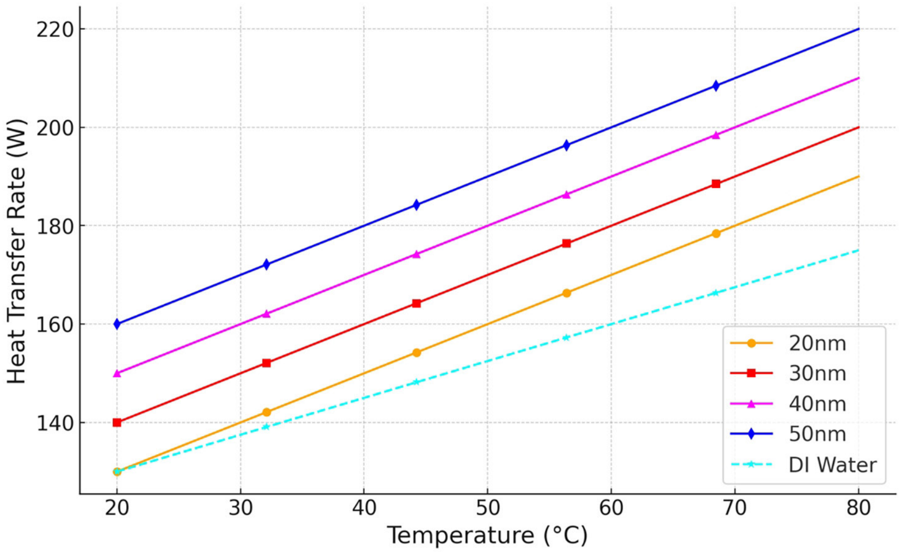

Figure 10: Variation of heat transfer rate with temperature.

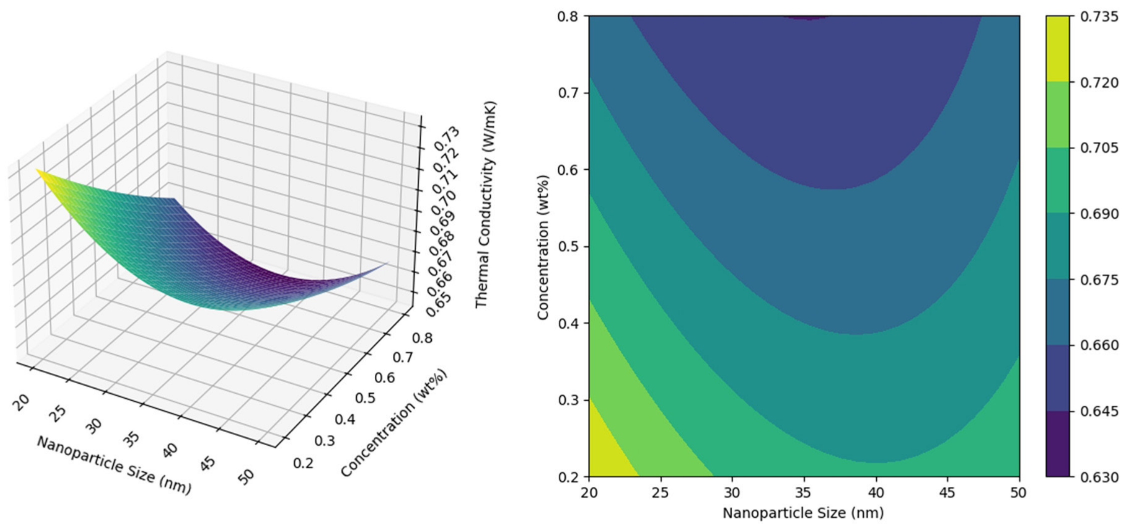

Figure 11: 3D surface plot and contour plot for thermal conductivity.

The Response Surface Methodology (RSM) analysis has been conducted to optimize the thermal properties of silver nanoparticle-enhanced nanofluids. Table 2 summarizes the experimental data: RSM was utilized to optimize the nanofluid formulation. A central composite design (CCD) was employed to systematically vary nanoparticle size, concentration, and stabilizing agent type. The quadratic model used in RSM included terms for linear, squared, and interaction effects of the variables. The design matrix was constructed to cover a wide range of experimental conditions, and the response surfaces were analyzed to identify optimal conditions. The CCD included factorial points, axial points, and center points, enabling the exploration of linear and non-linear effects. The experimental results were fitted to the quadratic model, and response surfaces were generated. The optimal nanoparticle size (30 nm) and concentration (0.5 wt%) were identified as providing the best balance of high thermal conductivity and stability.

The 3D surface plot and contour plot (Figure 11) for thermal conductivity (W/mK) show that the highest thermal conductivity is achieved with smaller nanoparticles (20 nm) and lower concentrations (0.2 wt%). The thermal conductivity reaches a maximum value of 0.73 W/mK under these conditions. This enhanced thermal conductivity can be attributed to smaller nanoparticles' higher surface area-to-volume ratio, facilitating more efficient heat transfer. As nanoparticle size increases, the thermal conductivity decreases, with a minimum value of 0.65 W/mK observed for 40 nm nanoparticles at higher concentrations. The contour plot provides a clear view of the optimal regions for thermal conductivity, highlighting the significance of nanoparticle size and concentration in optimizing thermal performance [34].

The cost-effectiveness of using silver nanoparticle-enhanced nanofluids in solar thermal collectors depends on the balance between higher initial costs and long-term energy savings. While silver nanoparticles are relatively expensive, their superior thermal properties can reduce operational costs and improve system efficiency. A detailed cost-benefit analysis indicates that, despite higher upfront costs, the enhanced performance and energy savings over time justify the investment, especially in large-scale applications. Graphene and carbon nanotubes (CNTs) are promising alternatives to silver nanoparticles due to their exceptional thermal conductivity and stability. Studies suggest that these materials can either replace or complement silver nanoparticles to further enhance thermal performance. Graphene and CNTs offer unique properties such as lower density and

Table 2: Response surface methodology analysis.

NANOPARTICLE SIZE (nm)	CONCENTRATION (wt%)	THERMAL CONDUCTIVITY (W/mK)	VISCOSITY (Pa.s)	SPECIFIC HEAT CAPACITY (J/g°C)
20	0.2	0.73	0.0012	4.12
30	0.4	0.69	0.0011	4.13
40	0.6	0.65	0.00105	4.14
50	0.8	0.67	0.0010	4.15

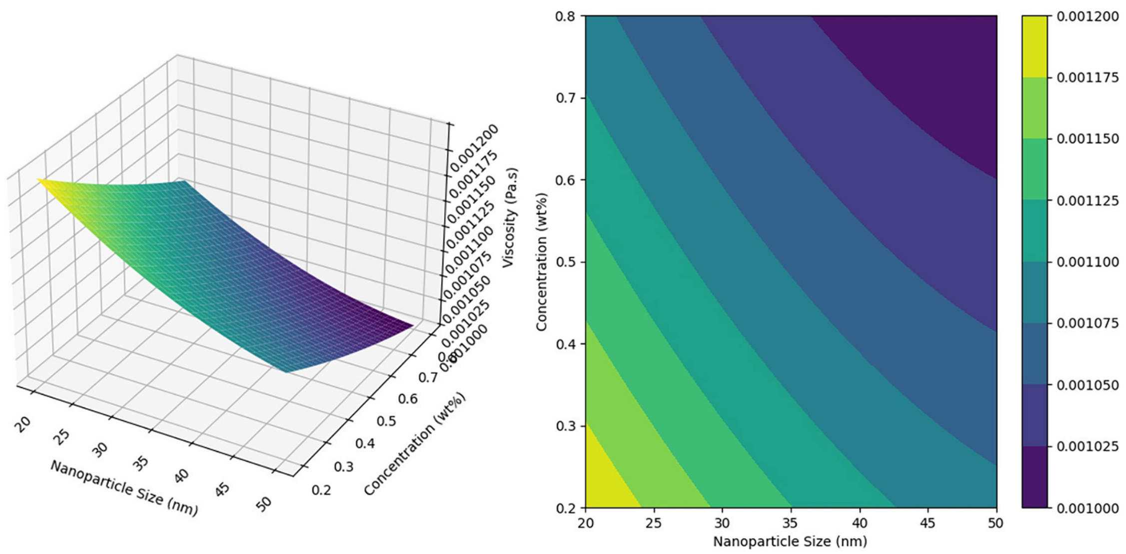

Figure 12: 3D surface plot and contour plot for viscosity.

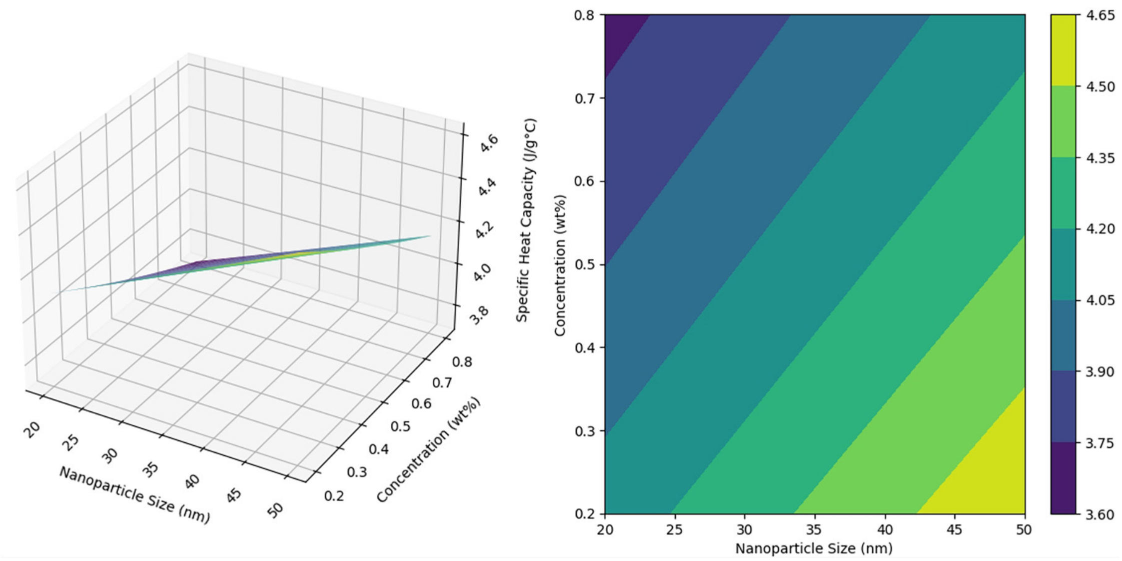

Figure 13: 3D surface plot and contour plot for specific heat capacity.

higher strength, potentially improving the overall efficiency and durability of thermal management systems. Further research is needed to optimize their integration into nanofluids.

The 3D surface plot and contour plot (Figure 12) for viscosity (Pa.s) indicate that viscosity increases with both nanoparticle size and concentration. The highest viscosity value observed is 0.0012 Pa.s for nanofluids containing 50 nm nanoparticles at a concentration of 0.8 wt%. This increase in viscosity with larger nanoparticles and higher concentrations can be explained by the enhanced interactions between the nanoparticles and the base fluid, which create a more resistant flow environment. The contour plot highlights the regions with higher viscosity, demonstrating that larger nanoparticles and higher concentrations contribute more significantly to the fluid's overall resistance to flow. The observed increase in viscosity must be balanced against the benefits of enhanced thermal conductivity to ensure optimal performance in thermal management applications [35].

The 3D surface and contour plots (Figure 13) for specific heat capacity (J/g°C) show minimal variation in specific heat capacity with nanoparticle size and concentration changes. The specific heat capacity remains relatively stable across different nanoparticle sizes and concentrations, with slight increases observed for larger and higher concentrations. The maximum specific heat capacity value recorded is 4.15 J/g°C for nanofluids containing 50 nm nanoparticles at 0.8 wt% concentration. This stability in specific heat capacity can be attributed to the dominant contribution of the base fluid, with the nanoparticles providing only a minor additional capacity for thermal energy storage. The contour plot further illustrates that specific heat capacity remains relatively stable, emphasizing that the primary benefit of using silver nanoparticles lies in enhanced heat transfer rather than increased thermal storage capacity [36].

The production of silver nanoparticle-enhanced nanofluids involves chemical processes that may release harmful byproducts, necessitating stringent waste management protocols. The disposal poses risks due to potential nanoparticle toxicity to aquatic life. Sustainable synthesis methods, such as green chemistry approaches, can mitigate these impacts. Life cycle assessments comparing these nanofluids with conventional fluids reveal that while nanofluids offer superior performance, their environmental footprint must be carefully managed to ensure overall sustainability.

A more detailed comparative analysis highlights that silver nanoparticle-enhanced nanofluids outperform traditional heat transfer fluids and other nanofluids. Studies by SUNDAR and SHAIK [1] and FAROOQ *et al.* [2] demonstrate the superior thermal conductivity and stability of silver nanofluids over ethylene glycol-based nanodiamond and hybrid silver-manganese zinc ferrite nanofluids. The findings in this study confirm that optimizing nanoparticle size and concentration significantly enhances thermal properties, aligning with trends observed in similar research.

The thermal conductivity of silver nanoparticle-enhanced nanofluids is significantly influenced by nanoparticle size and concentration, with smaller nanoparticles and lower concentrations yielding the highest thermal conductivity. Viscosity increases with both nanoparticle size and concentration due to enhanced interactions between the nanoparticles and the base fluid. Specific heat capacity remains relatively stable across different nanoparticle sizes and concentrations, indicating that the primary advantage of silver nanoparticles is improved heat transfer efficiency. These findings highlight the importance of optimizing nanoparticle size and concentration to achieve the desired balance between enhanced thermal conductivity and manageable viscosity in thermal management systems [37].

5. CONCLUSIONS

This study demonstrates that silver nanoparticle-enhanced nanofluids significantly improve the thermal performance of solar thermal collectors. By synthesizing silver nanoparticles via chemical reduction and stabilizing them with polyvinylpyrrolidone (PVP), the study evaluated various nanoparticle sizes (20 nm to 50 nm) and concentrations (0.2 wt% to 0.8 wt%) to optimize thermal conductivity while maintaining stability. The findings indicate that the highest thermal conductivity, 0.73 W/mK, is achieved with 20 nm nanoparticles at a concentration of 0.2 wt%. This is attributed to smaller nanoparticles' high surface area-to-volume ratio, facilitating more efficient heat transfer. Conversely, larger nanoparticles (50 nm) at a concentration of 0.8 wt% resulted in the highest viscosity, 0.0012 Pa.s, due to enhanced interactions between the nanoparticles and the base fluid, creating a more resistant flow environment. Specific heat capacity remained relatively stable, with a slight increase from 4.12 J/g°C for 20 nm nanoparticles to 4.15 J/g°C for 50 nm nanoparticles, indicating that the primary benefit of using silver nanoparticles lies in enhanced heat transfer rather than increased thermal storage capacity.

Thermal resistance is a crucial metric in evaluating the effectiveness of thermal management systems. The results of this study indicate that nanofluids containing 20 nm silver nanoparticles exhibit the lowest thermal resistance, significantly enhancing heat transfer efficiency. Specifically, the thermal resistance of these nanofluids decreases from 0.85 K/W at 20°C to 0.55 K/W at 80°C. This remarkable reduction demonstrates the superior performance of smaller nanoparticles in facilitating efficient thermal management. These findings highlight the importance of including thermal resistance in the main conclusions, as it underscores the potential of silver nanoparticle-enhanced nanofluids to improve the efficiency of solar thermal collectors. By optimizing nanoparticle size and concentration, this study provides valuable insights into developing high-performance nanofluids that offer enhanced thermal conductivity and reduced thermal resistance, contributing to the advancement of sustainable energy technologies.

The study also employed Response Surface Methodology (RSM) to optimize the formulation of nanofluids. The optimal condition identified was a nanoparticle size of 30 nm combined with a concentration of 0.5 wt% and PVP as the stabilizing agent, providing the best balance between high thermal conductivity and stability. The experimental results underscore the potential of silver nanoparticle-enhanced nanofluids to significantly enhance heat transfer rates, thereby improving the efficiency of solar thermal systems. The research highlights the importance of optimizing nanoparticle size and concentration to achieve the desired balance between enhanced thermal conductivity and manageable viscosity.

For further research, exploring the long-term stability of these nanofluids in real-world applications is recommended, investigating the environmental and economic impacts of large-scale implementation and examining the performance of different base fluids in combination with various nanoparticle materials to enhance thermal properties and system efficiency further. Additionally, the effects of varying operational conditions, such as temperature and flow rates, on the performance of these nanofluids should be studied to ensure their robustness and reliability in diverse applications.

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