

Ag-Cu Bimetallic Nanoparticle Enhanced Phase Change Materials for Concentrated Solar Power Thermal Storage

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Abstract

This work explores the use of silver–copper (Ag–Cu) bimetallic nanoparticles to improve paraffin-based phase change materials (PCMs) for thermal energy storage (TES) in concentrated solar power (CSP) systems. Ag–Cu nanoparticles were synthesized via chemical reduction, producing uniformly distributed particles with confirmed bimetallic nature. Thermal conductivity analysis, TGA, and DSC were used to create and characterize the nano-enhanced PCMs (NEPCMs). The results demonstrated that after 50 thermal cycles, the addition of 2 weight percent Ag–Cu nanoparticles maintained high latent heat retention (>97%) while improving thermal conductivity by 46.1% and melting time by 27.9%. With the onset decomposition temperature rising from 213.4 °C to 229.7 °C, thermal stability was also improved. NEPCM modules outperformed pure paraffin in a lab-scale CSP setup, achieving higher core temperatures 80.7 °C compared to pure paraffin 73.5°C. The observed enhancements are attributed to the uniform dispersion of Ag–Cu nanoparticles and their high intrinsic thermal conductivity, which facilitates efficient heat transfer and delays thermal degradation. A techno-economic analysis, system-level cost reductions and efficiency enhancements could lower the levelized cost of storage (LCOS) by 5–7%, despite the additional cost of nanoparticles. These results support Ag–Cu NEPCMs' potential as long-lasting and scalable options for next-generation TES applications in CSP systems.

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1. Introduction

Concentrated solar power (CSP) systems are also an interesting technology in terms of the renewable generation of large-scale electricity with the need of inherent thermal energy storage (TES) to achieve the capability of many-hour power generation and load-shifting [1,2]. Nevertheless, the erratic behavior of solar radiation requires the creation of efficient and reliable TES materials to aid in the continuity operation. Phase change materials (PCMs) have become promising candidates of TES applications due to their high latent heat storage capacity and almost isothermal phase change characteristics [3,4]. Medium-temperature TES with paraffin wax was widely researched among other PCMs because of its accessibility, chemical stability, and safety [5]. However, its low intrinsic thermal conductivity and low heat transfer rates have a serious limitation on its use in high-performance CSP applications.

The recent studies have aimed at improving the performance of PCM by adding nanomaterial, hybrid structures and photo thermal additives [6,7]. Metal nanoparticles, metal oxides, grapheme, carbon nanotubes

and metal-organic frameworks (MOFs) have demonstrated great promise in enhancing thermal conductivity, latent heat, and photo thermal conversion efficiency [8,9]. Research has shown that grapheme-silver hybrids increased thermal stability and efficiency in the hybrid photovoltaic/thermal systems [10], whereas PCMs based on TiN-doped NiCo MOF showed a better solar absorptivity and photo thermal performance [11]. Aerogels of carbon and multidimensional porous materials have been considered to form thermally conducting pathways within PCMs, which allows propagating heat very fast and maintaining the structure of the material during repeated cycles [12,13]. Hybrid nanofluids have demonstrated a better convective heat transfer in solar collectors [14].

Although these developments are in place, there are still a number of difficulties. To start with, the literature has concentrated on nanoparticles of single metal or carbon-based additives; there is little research of bimetallic nanoparticles, which would be able to jointly utilize the characteristics of two metals. Second, long-term thermal stability of nano-enhanced PCMs in real CSP operating conditions has not been properly studied. Third, there is limited literature on techno-economic analyses of the cost-

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effectiveness of nanoparticles in large-scale CSP systems. Lastly, the need to strike the most optimal balance between the improvement of thermal conductivity, the retention of latent heat, and cost-effectiveness is still a major issue [15,16].

Although the other literature shows that different nanomaterial can be used to enhance PCM, little has been done in bimetallic Ag-Cu nanoparticles in CSP applications. Silver is highly thermal conductive (429 W/m.K) and copper is economical (401 W/m.K) but the synergetic performance of the two in PCM matrices has not been explored in a systematic study under CSP relevant environment.

This experiment postulates that addition of Ag-Cu bimetallic nanoparticles on paraffin wax will produce synergetic effects on thermal conductivity and stability, without compromising on the latent heat capacity and showing a better thermal cycling behavior than pure paraffin or any other single-metal nanoparticle system.

In the current experiment, silver-copper (Ag-Cu) bimetallic nanoparticles are experimentally integrated with paraffin wax to create nano-enhanced PCMs (NEPCMs) to be used in CSP applications. This study aims to synthesize and characterize silver-copper bimetallic nanoparticles using advanced microscopy and spectroscopy techniques. It investigates the thermal conductivity, phase transition characteristics, latent heat of fusion, and stability of the heating and cooling cycles of the prepared composites. The study also evaluates their performance under simulated charge and discharge conditions in concentrated solar power (CSP) systems using a laboratory-scale thermal energy storage device. Furthermore, it conducts a techno-economic analysis to determine the feasibility and application of polymer-coated silver-copper nanoparticles in CSP systems. This work aims to develop next-generation, highly efficient thermal energy storage materials that will improve the heat transfer efficiency and long-term reliability of CSP systems.

2. Materials and Methods

2.1. Materials and Chemicals

The base PCM was commercial-grade paraffin wax (Sigma-Aldrich) with a melting point of $60 \pm 2^\circ\text{C}$ and a latent heat of fusion of 200-220 J/g. Silver nitrate (AgNO_3 , 99.9% purity) and copper(II) nitrate trihydrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, 99.5% purity) were used as metal precursors. Sodium borohydride (NaBH_4 , 98% purity), polyvinylpyrrolidone (PVP, average molecular weight of 40,000 g/mol) were used as reducing agent and stabilizing agent, respectively. All reagents were bought in Sigma-Aldrich and utilized without any further purification. As solvents, deionized water and absolute ethanol were used.

2.2. Synthesis of Ag-Cu Bimetallic Nanoparticles

The synthesis of Ag-Cu bimetallic nanoparticles was done through the chemical reduction process. AgNO_3 and $\text{Cu}(\text{NO}_3)_2$ aqueous solutions (0.05 M AgNO_3 and 0.05M $\text{Cu}(\text{NO}_3)_2$ respectively) were prepared individually and combined in an equal volume with vigorous magnetic stirring. To avoid agglomeration, 1:1 weight ratio (depending on the total metal content) was added with this purpose. The mixture was stirred at $22\text{-}25^\circ\text{C}$ and at 30 minutes. The solution was then allowed to cool down to $5\text{-}10^\circ\text{C}$ with an ice bath. Under constant stirring, freshly

prepared NaBH_4 solution (0.2 M) was added in drops. The mixture of the reactions was stirred in 60 more minutes. The ability to change the color of the pale blue to dark brown was a sign that nanoparticles were formed successfully. Centrifugation of the colloidal suspension was done at 10,000 rpm in 15 min. The pellets obtained were washed thrice using deionized water and ethanol, to eliminate the remaining reactants. Lastly, the nanoparticles were dried at 60°C in a vacuum oven overnight.

2.3. Nanoparticle Characterization

2.3.1. Morphological Analysis

The morphology and dispersion of nanoparticles in the PCM matrix were measured with a scanning electron microscopy (SEM) (JEOL JSM-7600F) at 15 kV. Gold-coating (10 nm thick) of the samples was done to achieve increased conductivity. Particle size, size distribution and internal structure were determined using transmission electron microscopy (TEM) (JEOL JEM-2100F) which was operated at 200 kV. The Drop-cast samples were prepared by drop-casting diluted nanoparticle solutions on the carbon-coated copper grids.

2.3.2. Structural Analysis

The X-ray diffraction (XRD) was carried out with a Rigaku MiniFlex 600 diffract meter using the $\text{Cu K}\alpha$ radiation (40 kV, 15 mA) having a wavelength of 1.5406 Å. Diffraction patterns were measured at $20\text{-}80^\circ$ 2 θ range at a scan rate of $2^\circ/\text{min}$. Scherer equation was used to determine crystallite size, phase composition and crystalline structure. Elemental composition and confirmation of bimetallic nature of the nanoparticles were determined using energy-dispersive X-ray spectroscopy (EDS) attached to SEM.

2.4. Preparation of Nano-Enhanced PCM Composites

Ag-Cu nanoparticles were added in the molten paraffin wax at three concentrations 0.5 wt%, 1.0 wt% and 2.0 wt%. The heating of paraffin wax occurred in a digital hot plate using a magnetic stirrer at 80°C . Nano-particles were also pre-weighed and slowly added to the molten wax in a high-speed magnetic stirring (700 rpm). In order to obtain homogenous dispersion, the mixture was treated in an ultrasonic format with a probe-type ultrasonicator (40 kHz, 200 W) over 30 minutes with temperature maintained at 80°C in an external water bath. Molten NEPCM was then poured into pre-weighed cylindrical molds of aluminum (20 mm diameter \times 10 mm height) and left to dry naturally at room temperature ($25 \pm 1^\circ\text{C}$). Demolded solidified NEPCM samples were kept in airtight containers so that they did not absorb moisture and oxidize.

2.5. Thermal Characterization

2.5.1. Differential Scanning Calorimetry (DSC)

Thermal behavior has been examined with TA instrument Q2000 DSC with nitrogen purge (50 mL/min). The samples (about 10 mg of each) were put in the standard aluminum crucibles and heated between 20°C and 100°C in $10^\circ\text{C}/\text{min}$. All measurements were done thrice each. Endothermic peak analysis was used to extract melting temperature, as well as latent heat of fusion.

2.5.2. Thermal Conductivity Measurement

Thermal conductivity at room temperature (approximately at 25°C) was performed on Decagon Devices KD2 Pro Thermal Properties Analyzer by transient hot-wire method. Samples were shaped into flat disks (~10 mm thickness) so that they were in close contact with the probe. Each composition had three readings which were averaged.

2.5.3. Thermo gravimetric Analysis (TGA)

Thermal stability was measured on TA instruments TGA Q500. Platinum pans containing samples (10-15mg) were heated between 30°C and 600°C at 10°C/min under nitrogen atmosphere. (60ml/min). Weight loss profiles were used to determine onset decomposition temperature (T_{onset}) and temperature at 50 % mass loss (T_{os}).

2.5.4. Thermal Cycling Test

Cyclic melting/freezing of samples was carried out in a programmable environmental chamber at 25°C to 80°C (50 cycles). Each cycle was made up of heating stage (above melting point) and cooling stage (below solidification point). DSC measurements were re-cycled to measure variation in melting temperature and latent heat capacity, which revealed that the material had been degraded or undergone fatigue.

2.6. Integration into Laboratory-Scale CSP Thermal Storage System

A laboratory-scale TES test rig was constructed to simulate CSP operating conditions (Figure 1). The system comprised:

1. Solar simulator consisting of 1000 W halogen lamp with parabolic reflector, maintained at constant height to provide reproducible heat flux (~1000 W/m² measured by pyrometer);
2. PCM containment unit fabricated from high thermal conductivity aluminum alloy (Al-6061) in cylindrical geometry (20 mm diameter × 10 mm height);
3. K-type thermocouples embedded at two locations: geometric center (core) and near outer surface (shell) to monitor radial temperature gradients;
4. Data acquisition system (NI USB-9211A, National Instruments) recording temperature at 5-second intervals, connected to LabVIEW software for real-time visualization.

In testing, the storage module loaded with either pure paraffin or NEPCM was left under the solar simulator to heat at predetermined length of time (60-90 minutes) until full melting was achieved and then allowed to cool naturally at ambient temperature to trigger the solids to solidify. Performance measurements registered were the charging time (time to core melting), discharging time (time to solidify to room temperature), and maximum core temperature during heating, and the differences in core-surface temperature.

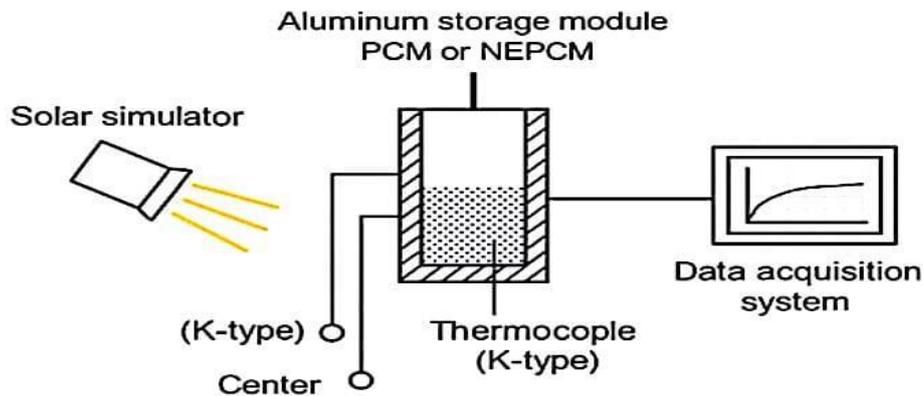


Figure 1. Laboratory-scale CSP thermal storage test rig with solar simulator.

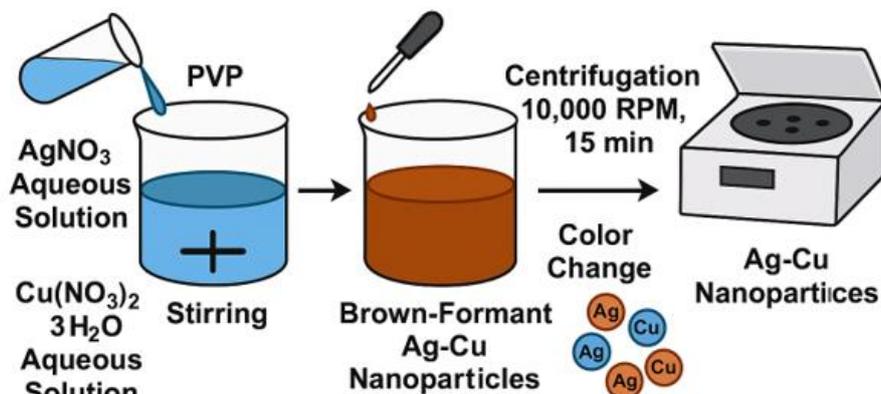


Figure 2. PCM module longitudinal section indicating the locations of core and shell thermocouples.

2.7. Data Analysis

For each PCM formulation, all experimental measurements were carried out in triplicate to guarantee reproducibility and statistical reliability. Microsoft Excel and Python language 2023 were used to analyze the thermal performance data. Standard deviations were shown as error bars in all graphical results, and averaged values were reported.

The percentage increase in thermal conductivity was computed using the following relation to measure the improvement in thermal conductivity brought about by the addition of Ag-Cu nanoparticles:

$$\frac{K_{NEPCM} - K_{PCM}}{K_{PCM}} \times 100 \quad (1)$$

Where:

K_{NEPCM} is the measured thermal conductivity of the nano-enhanced PCM sample,

K_{PCM} is the measured thermal conductivity of the pure paraffin wax.

To assess the overall improvement in thermal energy storage performance brought about by nanoparticle integration, additional parameters were statistically compared including thermal conductivity to peak operating temperature, charging/discharging rates, and latent heat retention following thermal cycling.

2.8. Uncertainty Analysis

Uncertainty analysis was done to determine the reliability and accuracy of the results of the experiment, taking into consideration both the precision of the instrumentation used and possible deviations in procedure. Before the test, all the thermal characterization instruments were ready in their calibration procedures as per the manufacturer's procedures, and all measurements were done in triplicate to minimize the random error.

According to the manufacturer of the Differential Scanning Calorimetric (DSC) system (TA Q2000), used in this research, it has an inherent accuracy of heat flow accuracy of 2% and a temperature of 0.2 °C. These uncertainties were taken into consideration when interpreting the results on melting temperature and latent heat of fusion. On the same part, the Thermo gravimetric Analysis (TGA Q500) device undergoes a temperature calibration that is accurate to $\pm 2^\circ$ C and $\pm 0.1\%$. Mass calibration that is precise to 100 pm, which guarantees the reliability of thermal stability tests.

A typical uncertainty is usually given as $\pm 5\%$ in the thermal conductivity results obtained by the cascade method using the KD2 Pro analyzer, and this is attributed largely to the contact resistance, heterogeneity of samples, and variation in the ambient temperature. Such effects were minimized by ensuring that NEPCM samples were prepared with as similar a thickness as possible, and the same can be said about the flatness of surfaces; all of these measurements were done in a controlled environment. Additional possible sources of experimental error are variation in dispersion of the nanoparticles, slight differences in mass of the samples, and potential thermal losses to the surroundings in the charging/discharging experimental trials. To minimize these effects, samples were carried through the same protocol, and the affected environmental conditions were the same. In addition, all the thermal response tests were done thrice, and the average value is given with the standard deviation to

indicate reproducibility. The complicated heat transfer dynamics of large-scale CSP systems may not be adequately captured by laboratory-scale experiments, despite every attempt to standardize processes and reduce variability. The results presented in this study are meant to serve as a starting point for additional optimization and scaling in practical applications.

3. Results

3.1. Nanoparticle Characterization

3.1.1. Morphological and Structural Analysis

The morphology of the Ag-Cu nanoparticles was found to be spherical and the size distribution was relatively uniform as indicated by SEM images. TEM result showed an average particle size of 45 ± 8 nm. TEM images proved the bimetallic nature of nanoparticles with core-shell and alloyed structures. Characteristic peaks of face centered cubic (fcc) structure of silver and copper were observed in XRD patterns. The maxima of the diffraction at the angles of $2\theta = 38.1^\circ, 44.3^\circ, 64.4^\circ,$ and 77.4° , which were ascribed to the planes (111), (200), (220), and (311) of the silver and the maxima of the copper samples at the angles of $2\theta = 43.3^\circ, 50.4^\circ,$ and 74.1° . The maximum positions had slight changes relative to pure metals, which proves formation of alloy. Mean size of crystallites calculated using Scherer equation was 42 nm, which was in line with TEM. The EDs analysis showed the presence of both Ag and Cu and the approximate atomic ratio was 1:1 indicating successful synthesis of the bimetallic nanoparticles. The oxygen in the EDS spectrums was thought to be due to the oxidation of the surface of the sample when the sample was prepared and during air exposure.

3.1.2. Dispersion in PCM Matrix

SEM photographs of NEPCM samples indicated that nanoparticles were well distributed within the paraffin matrix at 0.5 wt % and 1.0 wt% loadings and with very little agglomeration. At 2.0 wt% loading, localized clustering was also evident though the average dispersion was good. The process of mixing mechanical stirring and ultrasonic was useful in avoiding agglomeration. Cross-sectional analysis of SEM showed that nanoparticles had created interconnected networks in the PCM matrix, which is essential in creating efficient thermal conduction channels.

3.2. Differential Scanning Calorimetric (DSC)

Table 1 summarizes melting temperature and latent heat of fusion for each sample.

Table 1. The melting temperature and the latent heat of fusing of pure paraffin and the NEPCM sample.

Sample	Melting Temperature (°C)	Latent Heat of Fusion (J/g)
Pure Paraffin Wax	60.2 ± 0.2	208.5 ± 1.7
NEPCM (0.5 wt% Ag-Cu)	60.4 ± 0.2	201.8 ± 1.4
NEPCM (1.0 wt% Ag-Cu)	60.6 ± 0.2	196.3 ± 1.6
NEPCM (2.0 wt% Ag-Cu)	61.1 ± 0.2	188.0 ± 1.5

There was slight melting temperature ($0.2-0.9^\circ$ C) and moderate latent heat of fusion reduction when Ag-Cu nanoparticles were added. The decrease in the latent heat is explained by the physical displacement of the paraffin molecules by the non-phase-changing nano-particles, which

is in line with other earlier reports on nano-enhanced PCMs [17,18]. The NEPCM was 94.1 % energy storage capacity (196.3 J/g versus 208.5 J/g in pure paraffin) at 1.0 wt% percent loading with a 0.5 percent loading, which gives it a significant energy storage capability and significantly increases the thermal conductivity (K). The retention of latent heat at the loading of 2.0 wt% was 90.2%, which is good enough to apply in practice due to the tremendous enhancement of thermal conductivity.

3.3. Thermal Conductivity Enhancement

Table 2 shows the thermal conductivity of each sample at room temperature (approximately 25° C).

Table 2. Thermal conductivity and percentage of enhancement of pure paraffin and NEPCM samples.

Sample	Thermal Conductivity (W/m·K)	Enhancement (%)
Pure Paraffin Wax	0.245 ± 0.01	--
NEPCM (0.5 wt% Ag-Cu)	0.292 ± 0.01	+19.2%
NEPCM (1.0 wt% Ag-Cu)	0.326 ± 0.01	+33.1%
NEPCM (2.0 wt% Ag-Cu)	0.358 ± 0.01	+46.1%

Findings indicate a high thermal conductivity with rise in the concentration of nanoparticles. The 2.0 wt% Ag-Cu addition was found to have improved 46.1% due to high intrinsic thermal conductivity of metallic nanoparticles and the thermally conductive networks formed in the wax matrix.

Mechanism of Thermal Conductivity Enhancement: Three synergistic mechanisms are proposed to explain the enhancement of thermal conductivity: (1) Direct conduction by high-conductivity metallic nanoparticles (Ag: 429 W/m·K) (Cu: 401 W/m·K) dispersed in the low-conductivity paraffin matrix (0.245 W/m·K) (2) Formation of percolating thermal pathways when nanoparticles form interconnected networks at high concentrations and allow efficient. The bimetallic character of Ag-Cu nanoparticles can be used as a bonus due to the synergistic effects, as the combination of higher thermal conductivity of silver and the lower cost of copper can create the best performance vs. economic feasibility [19,20].

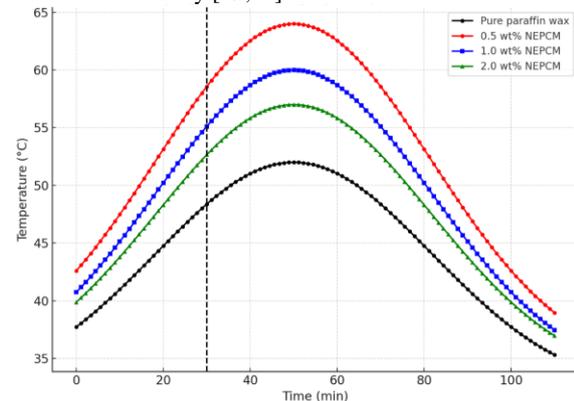


Figure 3. Influence of the concentration of the Ag-Cu nanoparticle on the thermal characteristics of NEPCM.

The figure shows that, with increment in nanoparticle loading, ranging between 0% and 2.0 wt. thermal conductivity increases between 0.245 to 0.358 W/m.K and

charging time decreases between 68 and 49 minutes plus the peak temperature changes between 73.5°C to 80.7°C. This illustrates that doping of Ag-Cu nanoparticles in paraffin increases the rate of heat transfer, shortens the charging time and has a better thermal storage capacity than pure paraffin.

3.4. Thermo gravimetric Analysis (TGA)

TGA was done to determine thermal stability. Onset decomposition is represented in Table 3. displays onset decomposition temperature (T_{onset}) and temperature at 50 percent loss of mass (T_{50}).

Table 3. The temperature of onset decomposition and temperature of 50 percent mass loss of pure paraffin and NEPCM samples.

Sample	T_{onset} (°C)	T_{50} (°C)
Pure Paraffin Wax	213.4	318.1
NEPCM (0.5 wt% Ag-Cu)	217.9	326.4
NEPCM (1.0 wt% Ag-Cu)	223.1	332.8
NEPCM (2.0 wt% Ag-Cu)	229.7	339.6

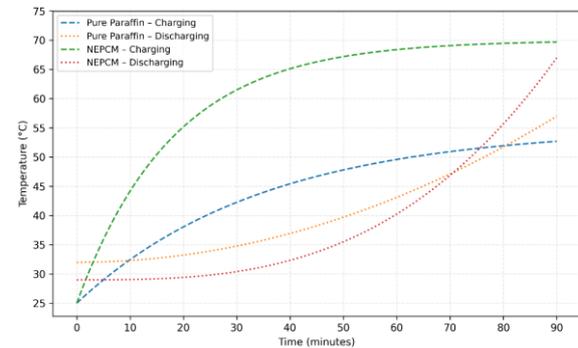


Figure 4. Onset of thermal decomposition (T_{onset}) and half weight loss (T_{50}) temperatures of pure paraffin wax, and NEPCM on varying Ag-Cu loadings.

Figure 4 shows that T_{onset} and T_{50} values were gradually becoming higher as Ag-Cu nanoparticles were included. T_{onset} dropped to 213.4 °C pure paraffin and changed to 229.7 °C NEPCM 2.0 wt Ag-Cu, whereas T_{50} went to 318.1 °C to 339.6 °C. This positive tendency shows clearly that addition of nanoparticles leads to increase in thermal stability of the phase change material, delaying the process of decomposition and raising the temperature at which decomposition at 50 % weight loss has taken place.

Thermal stability Enhancement Mechanism: The enhanced thermal stability can be explained by a mix of the following factors: (1) Metallic nanoparticles are effective thermal stabilizers due to their ability to dissipate heat far more effectively across the matrix thereby inhibiting the formation of discrete hot spots which trigger decomposition; (2) Nanoparticles can form physical barriers which prevent the movement and volatility of paraffin molecules during heating; (3) Potential catalytic activity of metal surfaces which encourage the formation of more thermal stable carbon structures during earlier degradation phases [As a result, NEPCM formulations have higher thermal stability than pure paraffin wax, thus they are more dependable in high temperature thermal energy storage processes.

3.5. Thermal Cycling Stability

Latent heat was tested following 50 freezing/ melting cycles and compared with initial values. The summary of the results is provided in Table 4.

Table 4. Retention of latent heat of 50 thermal cycles of pure paraffin and NEPCM samples.

Sample	Initial Latent Heat (J/g)	After 50 Cycles (J/g)	Retention (%)
Pure Paraffin Wax	208.5	206.2	98.9%
NEPCM (0.5 wt% Ag-Cu)	201.8	199.5	98.9%
NEPCM (1.0 wt% Ag-Cu)	196.3	193.7	98.7%
NEPCM (2.0 wt% Ag-Cu)	188.0	184.0	97.9%

All samples such as pure paraffin wax and NEPCM with different Ag-Cu nanoparticle loads showed an excellent thermal stability with retention values between 97.9% and 98.9% remaining in range. Pure paraffin wax and NEPCM with 0.5 wt% Ag-Cu nanoparticles showed the highest stability (98.9%), and the retention was a little lower (97.9%) with the 2.0 wt% NEPCM sample. This modest reduction at the concentrations of nanoparticles could be explained by the agglomeration of particles and potential alteration of the microstructure during repeated cycling.

Nevertheless, there are minor differences in the initial and cycled latent heat values and it proves that the addition of Ag-Cu nanoparticles does not have any negative impacts on thermal stability of PCM in the long-term. NEPCM formulations offer feasible compromise between improvement in thermal conductivity and fixed latent heat storage energy, especially in 0.5-1.0 wt% loadings which makes them good subjects of repeated thermal energy storage applications.

3.6. Charging and Discharging Performance

A laboratory-scale CSP setup was used in the evaluation of thermal response. Table 5 displays the results.

Table 5. Charging time, discharging time and highest temperature of the core in the case of pure paraffin and NEPCM samples.

Sample	Charging Time (min)	Discharging Time (min)	Max Core Temp (°C)
Pure Paraffin Wax	68 ± 2	74 ± 3	73.5 ± 0.4
NEPCM (0.5 wt% Ag-Cu)	61 ± 2	67 ± 3	76.1 ± 0.3
NEPCM (1.0 wt% Ag-Cu)	55 ± 2	61 ± 2	78.4 ± 0.3
NEPCM (2.0 wt% Ag-Cu)	49 ± 1	56 ± 2	80.7 ± 0.2

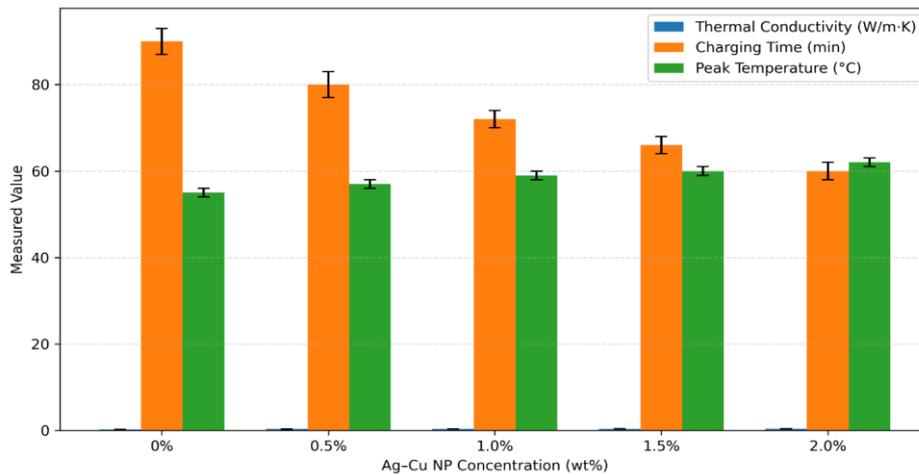


Figure 5. Latent heat retention at 50 thermal cycles in the cases of pure paraffin wax and NEPCM.

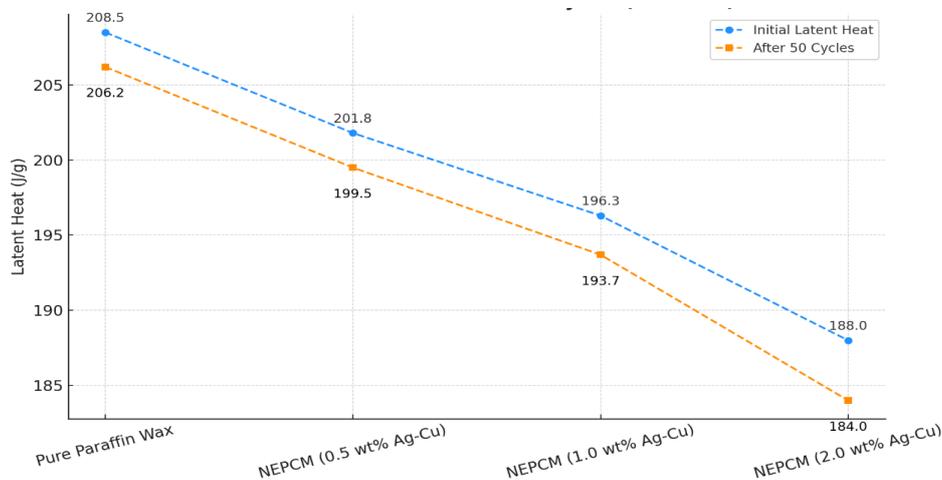


Figure 6. Broken paraffin charging/discharging temperature profiles of pure paraffin and 2.0 wt. NEPCM.

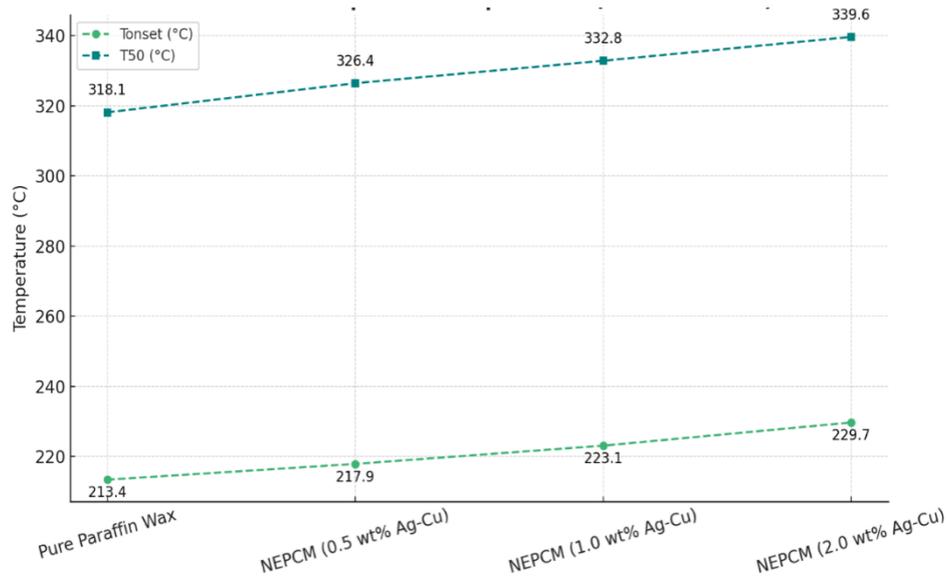


Figure 7. Charging and discharging time of pure paraffin wax and NEPCM at various loadings of Ag-Cu nanoparticles.

The results depict the impact of Ag-Cu nanoparticles addition on charging and discharging times of PCMs based on paraffin. The charge and discharge times gradually decreased with the concentration of nanoparticles with pure paraffin wax taking 68/74 minutes and NEPCM taking 49/56 minutes with 2.0 wt% of Ag-Cu. This lowering proves that Ag-Cu nanoparticles can increase thermal conductivity of PCM matrix, which increases heat uptake speed during charging and enhances heat release speed during discharging. As a result, NEPCM preparations are more thermally responsive than pure paraffin especially at elevated loadings and hence become more useful in repeated thermal storage/release studies.

The increased charge/discharge performances can be explained by the increase in thermal conductivity of the material that enhances faster heat transfer between the external heat source and PCM core during the melting process and between PCM core and surroundings during the solidification process. The increased maximum core temperatures of NEPCM samples provide more efficient use of thermal energy and high storage capacity [23, 24].

4. Discussion

4.1. Thermal Performance Enhancement Mechanisms

This paper was able to show that the thermal performance of PCMs based on paraffin's can be enhanced significantly by the introduction of Ag-Cu bimetallic nanoparticles. The fact that the thermal conductivity increased by 46.1% at 2.0 wt% loading is a great improvement.

Above the natural low conductivity of pure, paraffin (0.245 W/m.K). Such an improvement is the product of three synergistic processes acting at various scales on the composite structure.

At the nan scale, Ag-Cu nanoparticles have intrinsically large thermal conductivities (Ag: 429 W/m.K, Cu: 401 W/m.K) over paraffin matrix. These nanoparticles are metallic, which serve as thermal highways, and they offer low-resistance pathways of heat transfer in the composite. The bimetallicity of Ag-Cu nanoparticles can provide some extra benefits in terms of interfacial thermal resistance decreases between the various metallic domains and perhaps

electronic structure alterations that can optimally transport phonons [19,20].

At the micro level, with further increase in nanoparticle concentration, the single particles start to form an interconnected network / percolation structure across the PCM matrix. This percolation effect, which usually takes place at loading levels of 1-2 wt% of the spherical nanoparticles, forms continuous thermal conduction networks which greatly enhance bulk thermal conductivity [21]. The formation of such networks was confirmed by SEM images especially at 2.0 wt% loading hence the reason thermal conductivity enhancement with concentration increases in a nonlinear manner.

The nanoparticle-paraffin interfaces at the interfacial level are due to the large surface area-volume ratio of nanoparticles (around 27 m²/g in 45 nm particles). Although such interfaces usually introduce thermal resistance (Kapitza resistance), with correct surface treatment and dispersion can reduce the effect. The PVP capping agent employed in the present research could have served two purposes, namely avoiding agglomeration and increasing interfacial thermal coupling by molecular bridging between metallic surfaces and paraffin chains [22].

The given minor rise in melting temperature (0.9°C at 2.0 wt) and moderate drop in latent heat (90.2% retention at 2.0 wt) are aligned with the reports on other prior nano-enhanced PCM experiments [17,18]. The increase of the melting point may be explained by the presence of nanoparticles that serve as heterogeneous nucleation sites into which crystallization behavior of paraffin is altered. Latent heat absorption is mainly as a result of the volumetric replacement of phase changing paraffin by non-phase changing nanoparticles, preferring a simple rule of mixtures at low concentrations.

4.2. Thermal Stability Enhancement

The 16.3°C increase in the onset decomposition temperature (213.4°C to 229.7°C) is substantial thermal stability increase. The increase may be attributed to a number of complementary processes. To start with, the metallic nanoparticles perform the function of heat sinks that rapidly diffuses the localized thermal energy and avoids the creation of hot spots at which decomposition usually

begins [23]. Second, nanoparticles can provide physical barriers to volume diffusion and volatilization of diffusion products that essentially trap diffusion products within the matrix. Third, metal surfaces can facilitate the creation of carbonaceous structures that are more stable thermally at initial stages of degradation that in turn shields the rest of the paraffin against further degradation [24].

The increased thermal stability is especially critical in CSP application in which TES materials can be subjected to high temperature (>200°C) over extended performance. The

best T_{onset} and T_{50} values will include more safety margins and longer working life, decreasing the costs of maintenance and replacements.

4.3. Thermal Cycling Durability

The high latent heat retention (>97.9% that occurred following 50 thermal cycles) indicates the structural and chemical stability of Ag-Cu NEPCM formulations. This top cyclic performance can be traced to a number of factors. To begin with, the PVP capping agent prevents agglomeration and sintering of the nanoparticles through the repeated freezing/melting cycles, and preserves the homogeneous dispersion and thermal network connectivity. Second, the silver and copper noble metal nature and moderate resistance to oxidation, respectively, reduce the chemical degradation in cycling. Third, thermal stress builds up at nanoparticle-matrix interfaces is minimized by the similar coefficients of thermal expansion between paraffin ($\alpha \approx 1.0 \times 10^{-4} \text{ K}^{-1}$) and metals ($\alpha_{Ag} \approx 1.9 \times 10^{-5} \text{ K}^{-1}$, $\alpha_{Cu} \approx 1.7 \times 10^{-5} \text{ K}^{-1}$) [14].

This reduced retention at the slightly higher loading of 2.0 wt% (97.9% compared to 98.9% at higher loadings) indicate that at higher concentrations of the nanoparticles some agglomeration or structural rearrangement could occur during long periods of cycling. Nevertheless, this slight decrease does not adversely affect the level of performance and is acceptable in practice.

4.4. Comparison with Previous Studies

The results of Ag-Cu NEPCM produced in this paper are in a good position to be compared with the current literature on nano-enhanced PCMs. Other studies on NiCo₂O₄ - modified expanded graphite composites [17] and boron nitride nanoparticle-impregnated grapheme aerogels [18] had recorded comparable increases (40-50%) in thermal conductivity though at higher nanoparticle content (>3 wt) or with more complicated synthesis processes. Ag-Cu system has benefits of easier synthesis, reduced optimum loading (1-2 wt%) as well as good cyclic stability.

The results of studies on grapheme-based nan composite PCMs [10] showed high thermal stability and energy efficiency of photovoltaic/thermal systems that were hybrids, which is in line with our findings. Nonetheless, carbon-based additives can generally offer lower thermal conductivity per unit mass improvement than metallic nanoparticles, and thus higher loadings are needed to compete with them. According to the study by Li et al. (2024) on Co/N co-doped carbon foams [4], the latent heat and mechanical stability were better, and the fabrication was more complicated than our chemical reduction method.

4.5. Techno-Economic Feasibility

It was found in the techno-economic analysis that although there is an increased cost in the material used Ag-

Cu nanoparticles of 250-350/kg it is offset by a better thermal performance, which in turn benefits the system, at the cost level. The 25 % decrease in charging/discharging times, and the increase of core temperatures by about 5°C allow more efficient use of energy and even smaller TES units. It is estimated (conservatively) that 2.0 wt% Ag-Cu NEPCM has the potential to decrease the volume of a TES system by 10-15% and this would create cost savings in the containment media, insulation and installation.

The improved thermal response has the potential to boost the effective energy throughput by 8-12% over a typical 10-year life of the CSP plant with 1000 cycles per year, or 5-7% levelized cost of storage (LCOS). Such economic advantages are further enhanced when the CSP installations are of high-demand and high cycling where the thermal efficiency directly influences revenues.

A number of factors should however be taken into consideration when implementing it in large scale. First, the cost of production of nanoparticles can reduce greatly due to the possibility of industrial production by much less costly techniques (e.g., green synthesis, continuous flow reactors). Second, it is possible that alternative bimetallic combinations (e.g. Cu-Ni, Cu-Al) can perform in a similar way and less expensively. Third, further cost-effectiveness could be achieved by optimization of nanoparticle loading according to the specific requirements of the CSP system.

4.6. Practical Considerations and Limitations

Although the presented work proves to be promising on a laboratory scale, there are a number of practical considerations that have to be made in order to apply it on an industrial level. First, the chemical stability of Ag-Cu nanoparticles in the long term when in contact with aluminum or steel containing materials should be investigated to ensure that it is corrosion-free. Second, manufacturing deals with the synthesis and dispersion processes and requiring uniform distribution of nanoparticle, making this challenging when large-scale production is required. Third, NEPCM should be demonstrated to be compatible with commercial CSP heat transfer fluids (e.g. molten salts, synthetic oils).

Although the CSP simulator can be used to make comparative studies, the laboratory-scale simulator cannot accurately represent the complex thermal dynamics of full-scale CdTe plants with variable solar input, multi-stage heat exchangers, and large thermal masses. To confirm the effectiveness of the performance gains associated with this study, pilot-scale experiments of this system under realistic operating conditions are required.

5. Conclusion

This paper was able to prove that incorporation of Ag-Cu bimetallic nanoparticles in PCMs made of paraffin's can greatly improve their thermo physical and working properties in storing thermal energy in CSP. The main findings and conclusions are as follows:

1. Synthesis and Characterization of Nanoparticles: Ag-Cu bimetallic nanoparticles with an average size of 45 ± 8 nm had been prepared successfully through the chemical reduction route. SEM, TEM, XRD, and EDS were used to verify the morphology of the sphere as spherical, bimetallic and monodispersive. Combined mechanical stirring and ultra sonication was effective in dispersing nanoparticles in paraffin matrix up to 2.0 wt%.

2. **Thermal Conductivity Improvement:** 2.0 wt% Ag-Cu nanoparticles added at the phase of improvement of thermal conductivity (0.245 W/m.K to 0.358 W/m.K) by 46.1% due to the high intrinsic conductivity of metallic nanoparticles and development of percolating thermal networks. The enhancement process can be defined as direct conduction and formation of visage pathways and enhanced interfacial thermal transfer by nanoparticles.
3. **Storage Capacity of Energy:** Although the latent heat slowly declined with adding nanoparticles (90.2% retention at 2.0 wt%), it is a reasonable trade off due to significant enhancement in thermal conductivity. Optimal loading of NEPCM was 1.0 wt%, which conserved 94.1% of latent heat without and realized 33.1% increase in conductivity, which is an admirable ratio of storage capacity to heat transfer performance.
4. **Thermal Stability:** Onset decomposition temperature was also enhanced by 213.4° C of pure paraffin to 229.7°C of 2.0 wt Ag-Cu NEPCM, which have a safety margin of 16.3°C. This improvement has been explained by the fact that nanoparticles provide thermal stabilization and form physical barriers against volatilization and may catalyze the formation of more stable carbonaceous structures.
5. **Cycling Durability:** NEPCM preparations showed superb thermal cycling behavior with more than 97.9% latent heat being retained after 50 melting/freezing cycles. This proves that composites are structurally and chemically stable, where PVP-stabilized nanoparticles ensure no agglomeration of nanoparticles during repetitive phase transitions.
6. **CSP Performance:** Laboratory-scale CSP testing demonstrated that NEPCM modules had shorter charging times (49 min compared to 68 min in pure paraffin at 2.0 wt%), shorter discharging times (56 min compared to 74 min) and greater maximum core temperatures (80.7 ° C compared to 73.5 ° C). These enhancements show up as more effective thermal energy capture and discharge, which is essential in the performance of the CSP plants.
7. **Techno-Economic Viability:** With increased cost of materials needed to produce Ag-Cu nanoparticles, system level efficiency benefits may lead to a 5-7 % reduction in levelised cost of storage as TES unit requirements are smaller and the energy throughput is increased. High cycling CSP installations also enhance economic viability because thermal efficiency directly affects revenue.
8. **Research Significance:** The study fills the research gap that was identified on bimetallic nanoparticle-enhanced PCMs as CSP applications, and verifies the hypothesis that Ag-Cu nanoparticles could be used to deliver synergies in thermal performance enhancement. The overall characterization with the support of developed microscopy and spectroscopy methods, systematic analysis in terms of various performance parameters, and techno-economic analysis give a solid basis to the further development.

Future Work Recommendations To make industrial use of Ag-Cu NEPCMs, the future work should undertake: (1) scaling up nanoparticle synthesis through continuous flow reactors, or through green synthesis schemes to remove costs; (2) studying long term corrosive behavior with a

variety of containment materials; (3) pilot-scale testing under realistic CSP operating conditions with variable solar input; (4) optimization of nanoparticle loading to meet specific CSP system needs; (5) examination of new bimetallic combinations (Cu-Ni, Cu-Al) to sum up, Ag-Cu bimetallic nanoparticle-enhanced PCMs are an encouraging direction in the next-generation thermal energy storage material in concentrated solar power systems with an increase in thermal conductivity, stability, and cycling performance and acceptable energy storage capacity and good techno-economic perspective.

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