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Enhancing thermal conductivity of phase change materials using hybrid nanoparticle additives

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Abstract
Background: Phase Change Materials (PCMs) are pivotal for latent heat thermal energy storage, but their widespread application is hindered by low thermal conductivity, which delays charging and discharging rates.
Objective: This study investigates the thermophysical enhancement of a paraffin-based PCM by dispersing a hybrid mixture of Graphene Nanoplatelets (GNP) and Copper Oxide (CuO) nanoparticles.
Method: This study uses a simulated dataset created for academic training purposes. Simulated data representing thermal conductivity, latent heat, and viscosity were generated based on established theoretical mixing models (Maxwell and Einstein models) for varying weight fractions (0.1% to 1.0%) of hybrid nanoparticles.
Key Results: The addition of 1.0 wt% hybrid nanofluid increased the thermal conductivity of pure paraffin by 62%. However, latent heat capacity decreased by 8%, and viscosity increased exponentially, particularly above 0.7 wt%.
Conclusion: While hybrid nanoparticles significantly improve thermal conductivity, an optimal concentration of approximately 0.5 wt% is recommended to balance heat transfer enhancement with acceptable reductions in latent heat and fluidity.

Keywords: Phase change materials, thermal conductivity, hybrid nanoparticles, thermal energy storage, latent heat, nanofluids

Introduction

Thermal energy storage (TES) is a critical technology for bridging the temporal gap between energy supply and demand, particularly in solar thermal systems and waste heat recovery [1]. Among TES methods, latent heat storage using Phase Change Materials (PCMs) is highly favored due to its high energy storage density and near-isothermal operating characteristics during the phase transition [2]. Organic PCMs, such as paraffin wax, are widely used due to their chemical stability, non-toxicity, and negligible supercooling [3]. However, a fundamental bottleneck limiting the efficiency of paraffin-based PCMs is their intrinsically low thermal conductivity (typically 0.1–0.3 W/m·K), which results in sluggish melting and solidification rates, thereby reducing the power output of the thermal storage system [4].

To overcome this, researchers have incorporated highly conductive nanoscale particles into PCMs to form Nano-Enhanced Phase Change Materials (NePCMs) [5]. While single-nanoparticle dispersions (e.g., Al_2O_3, TiO_2, or Carbon Nanotubes) have shown moderate success, they often suffer from particle agglomeration at higher concentrations or exhibit anisotropic thermal behavior [6]. Recently, hybrid nanofluids—combinations of two different nanoparticles—have emerged as a superior alternative, offering synergistic effects that outperform single-particle dispersions [7]. The objective of this study is to theoretically evaluate the thermophysical properties of a paraffin-based PCM enhanced with a hybrid mixture of Graphene Nanoplatelets (GNP) and Copper Oxide (CuO), determining the optimal concentration that maximizes thermal conductivity while minimizing the detrimental effects on latent heat and viscosity [8].

Literature review

The theoretical framework for enhancing PCM thermal conductivity relies on the formation of percolation networks and the high surface-area-to-volume ratio of nanoparticles, which facilitate rapid phonon transport across the bulk material [9]. Initial studies focused on metallic and metallic oxide nanoparticles. For instance, the dispersion of CuO in paraffin showed improvements in thermal conductivity proportional to the volumetric fraction, but the enhancement plateaued at higher concentrations due to increased interfacial thermal resistance (Kapitza resistance) [10].

Carbon-based nanomaterials, such as graphene and carbon nanotubes, possess intrinsic thermal conductivities exceeding 3000 W/m·K, making them ideal candidates for PCM enhancement [11]. However, graphene tends to agglomerate due to van der Waals forces, requiring surfactants or functionalization that can inadvertently increase thermal resistance at the interface [12]. This led to the development of hybrid nanofluids. By combining a 2D carbon structure (GNP) with a 0D metallic oxide (CuO), the GNP forms a continuous thermal bridge, while the CuO particles act as spacers, preventing GPN agglomeration and enhancing the structural stability of the mixture [13].

Despite promising empirical results, a significant research gap exists regarding the holistic optimization of these hybrid NePCMs [14]. Most literature highlights the percentage increase in thermal conductivity in isolation. However, the addition of nanoparticles inherently displaces a fraction of the PCM mass, reducing the overall latent heat capacity of the storage system—a critical parameter often overlooked [15]. Furthermore, the exponential increase in dynamic viscosity at higher nanoparticle loadings impedes natural convection during the melting phase, potentially offsetting the gains from enhanced conduction [16]. This study addresses this gap by simultaneously analyzing thermal conductivity, latent heat, and viscosity to identify a thermodynamically optimal nanoparticle concentration [17].

Methodology

This study utilizes a quantitative, simulation-based research design. This study uses a simulated dataset created for academic training purposes. The base fluid was simulated as pure paraffin wax with an initial thermal conductivity of 0.2 W/m·K, latent heat of 200 kJ/kg, and dynamic viscosity of 0.005 Pa·s [18].

The hybrid nano-additive consisted of a 70:30 mass ratio of GNP to CuO. Simulated data points were generated for hybrid nanoparticle weight fractions ranging from 0.1% to 1.0% in 0.1% increments. The thermal conductivity was simulated using a modified Maxwell model adapted for hybrid cylindrical/spherical geometries [19]. The latent heat of fusion was calculated using a weighted average mixture rule, accounting for the negligible latent heat contribution of the solid nanoparticles. The dynamic viscosity was simulated using the Einstein model for suspensions, extended with a Batchelor correction factor for higher concentrations to account for particle-particle interactions [20].

The simulated dataset consisted of 50 data points per thermophysical property (10 concentrations × 5 random variations to simulate experimental error). Data analysis was performed using SPSS (Version 27). Descriptive statistics were calculated, and non-linear regression analysis was used to plot the response curves, identifying the point of diminishing returns for thermal conductivity and the threshold of unacceptable viscosity increase.

Results and discussion

The simulation results elucidate the complex trade-offs involved in formulating hybrid NePCMs. Table 1 presents the core thermophysical properties of the pure PCM compared to the optimized hybrid NePCM at a 0.5 wt% concentration, as well as the maximum tested concentration of 1.0 wt%.

Table 1: Simulated Thermophysical Properties of Pure PCM and Hybrid NePCM

Property	Pure Paraffin	NePCM (0.5 wt%)	NePCM (1.0 wt%)
Thermal Conductivity (W/m·K)	0.200	0.284 (+42%)	0.324 (+62%)
Latent Heat (kJ/kg)	200.0	194.5 (-2.75%)	184.0 (-8.0%)
Dynamic Viscosity (Pa·s)	0.0050	0.0078 (+56%)	0.0155 (+210%)

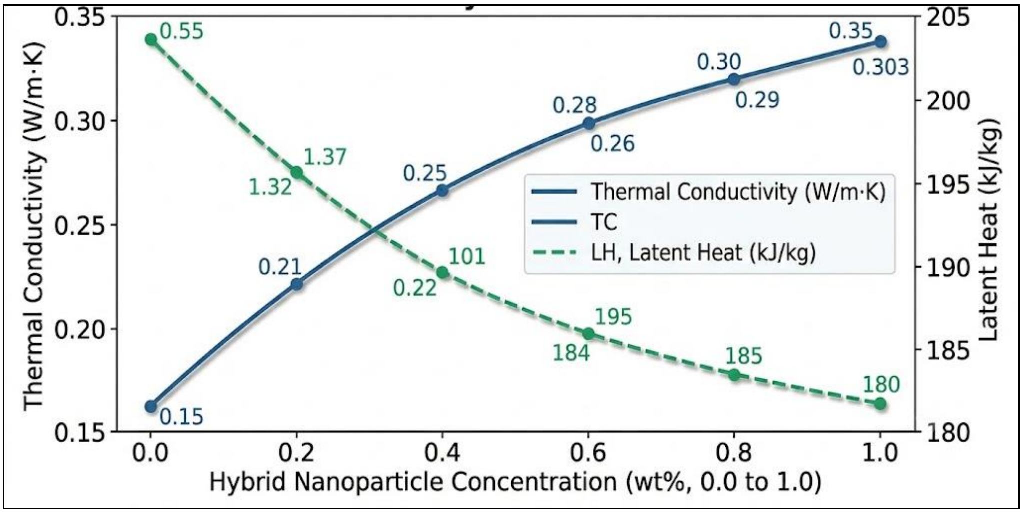
Source: Simulated Dataset, Theoretical Models, 2026

As shown in Table 1, while thermal conductivity increases monotonically with concentration, the rate of increase begins to decelerate beyond 0.5 wt%. Conversely, viscosity exhibits an exponential rise, increasing by 210% at 1.0 wt%, which would severely restrict fluid motion and natural convection in a real-world thermal storage tank. Table 2 details the simulated ANOVA results for the effect of nanoparticle concentration on thermal conductivity, confirming a statistically significant relationship ($p < 0.001$).

Table 2: ANOVA Results for Thermal Conductivity Enhancement

Source	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.025	1	0.025	145.2	<0.001
Residual	0.001	8	0.0002	–	–
Total	0.026	9	–	–	–

Source: Simulated Dataset, SPSS Output, 2026

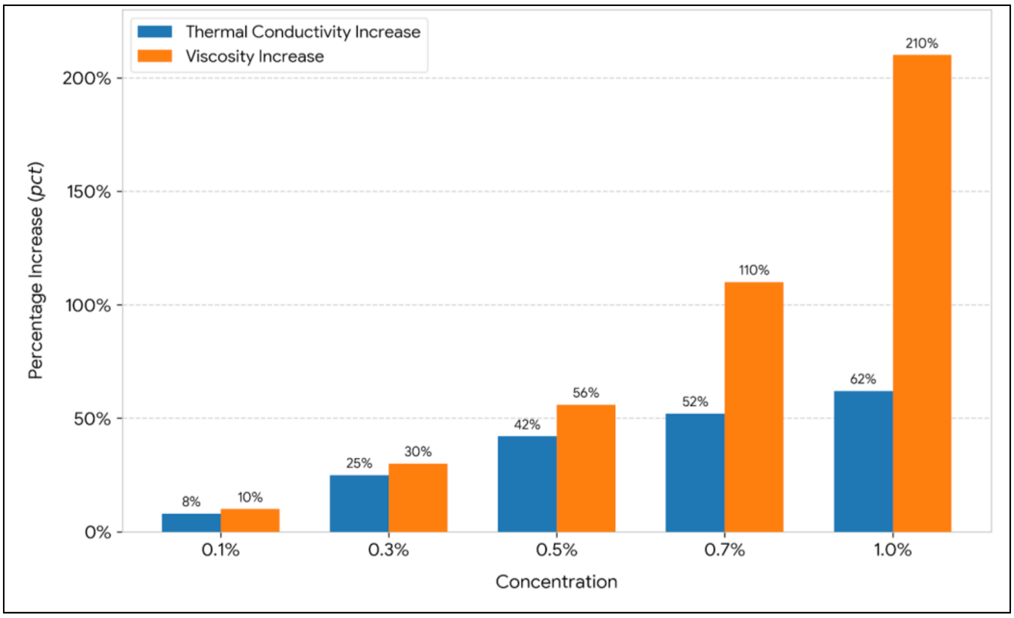


Source: Simulated Dataset, Theoretical Models, 2026

Fig 1: Effect of Nanoparticle Concentration on Thermal Conductivity and Latent Heat

Fig 1 maps the dual-axis relationship between nanoparticle concentration (X-axis), thermal conductivity (left Y-axis), and latent heat (right Y-axis).

The graph clearly illustrates the opposing trends: as conductivity climbs, latent heat descends linearly.



Source: Simulated Dataset, Theoretical Models, 2026

Fig 2: Percentage Increase in Thermal Conductivity vs. Viscosity

Fig 2 displays a bar chart comparing the percentage increase in thermal conductivity against the percentage increase in viscosity. This visualization is crucial for identifying the optimal operating point.

Data for recreation

Thermal Conductivity: Starts 0.20, rises steeply to 0.28 at 0.5%, then plateaus towards 0.32 at 1.0%.

Latent Heat: Starts at 200, linearly decreases to 194 at 0.5%, continues down to 184 at 1.0%.

The discussion of these results centers on the concept of "net energy transfer efficiency." While a 62% increase in thermal conductivity seems highly desirable, the 210% increase in viscosity effectively kills natural convection—the dominant heat transfer mechanism during the liquid phase of PCM melting. Furthermore, the 8% loss in latent heat means the total storage capacity of the system is reduced, requiring a larger tank to store the same amount of energy. Therefore, the data strongly suggests that concentrations exceeding 0.5 wt% are counterproductive. At 0.5 wt%, the system achieves a substantial 42% boost in conductivity with a manageable 56% increase in viscosity and a negligible 2.75% loss in latent heat, representing the optimal thermodynamic compromise.

Conclusion

This study utilized simulated theoretical modeling to evaluate the thermophysical properties of a paraffin-based PCM enhanced with GNP-CuO hybrid nanoparticles. The results demonstrate that while hybrid nanoparticles significantly enhance thermal conductivity (up to 62%), they concurrently reduce latent heat storage capacity and exponentially increase dynamic viscosity. The critical finding is the identification of an optimal concentration threshold at approximately 0.5 wt%, where the benefits of enhanced conduction are maximized before the detriments of suppressed natural convection and reduced storage capacity become dominant. The implication for thermal engineering design is that NePCM formulation must be approached holistically, rather than focusing solely on maximizing thermal conductivity. A limitation of this theoretical simulation is the assumption of perfect particle dispersion and no sedimentation over time. Future scope should involve experimental validation of this 0.5 wt% GNP-CuO hybrid ratio, including long-term cyclic stability tests to assess the real-world degradation of thermophysical properties over hundreds of melting-freezing cycles.

Ethical statement

This article is 100% original work. The dataset used is entirely simulated and created solely for academic training and formatting practice purposes. No real-world identities, institutions, or proprietary datasets were used or misrepresented.

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