ISSN 2350-1049

International Journal of Recent Research in Interdisciplinary Sciences (IJRRIS)
Vol. 12, Issue 2, pp: (1-10), Month: April - June 2025, Available at: www.paperpublications.org

A Control Volume Analysis of Energy Distribution on Nano-Enhanced Phase Change Material

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DOI: https://doi.org/10.5281/zenodo.15223406

Published Date: 15-April-2025

Abstract: **The growing global energy demand has led to research into effective energy storage technologies such as Thermal Energy Storage (TES) and Phase Change Materials (PCMs). This study explores the use of Nano-Enhanced Phase Change Materials (NEPCMs) to enhance thermal conductivity and overall performance. Results show that nanoparticle inclusion significantly improves thermal conductivity and energy distribution, especially at higher temperature differences. Future research should focus on the long-term stability and effects of different nanoparticle types and concentrations in energy storage systems.**

Keywords: **Heat transfer; Nano-Enhanced Phase Change Materials; Nanoparticle; Phase change materials; Solar thermal energy storage; Thermal energy storage.**

I. INTRODUCTION

The growing worldwide energy demand, combined with the need for sustainable energy solutions, has fueled research into effective energy storage technologies [25, 1]. Thermal Energy Storage (TES) is one of the most promising technologies in this field, as it can help balance energy supply and demand by storing extra energy during low-demand periods and releasing it when demand is high. Among the different TES approaches, Phase Change Materials (PCMs) have received a lot of attention due to their high energy storage density and ability to store and release energy at virtually constant temperatures during phase transition.

Nanoparticles, such as metals, metal oxides, carbon nanotubes or Single Walled Carbon Nanotube (SWCNT) and Multi Walled Carbon Nanotube (SWCNT) MWCNT, and graphene, exhibit unique properties compared to bulk solids, including a high aspect ratio and elevated thermal conductivity [18, 9]. For instance, the TC of MWCNT can exceed 3000 W/m.K, and a single layer of graphene can reach up to 5350 W/m.K, compared to the much lower TC of paraffin, a common PCM, which is about 0.305 W/m.K. The inclusion of nanoparticles has been shown to enhance both the TC and other thermophysical properties of PCMs.

PCMs can store large amounts of thermal energy in the form of latent heat during the phase change process, typically from solid to liquid and vice versa [12]. This property makes them highly efficient for use in TES systems. However, despite their advantages, PCMs face challenges related to their thermal conductivity, which is generally low, ranging between 0.1 and $0.7W/mK$. This low thermal conductivity restricts the rate of heat transfer within the material, leading to inefficiencies in thermal management and energy storage applications. Researchers have explored various strategies to enhance the thermal properties of PCMs. One of the most effective methods is the incorporation of nanoparticles into the PCM matrix, creating what is known as Nano-Enhanced Phase Change Materials (NEPCMs). Nanoparticles such as metals, metal oxides, carbon nanotubes (CNTs), and graphene have been used to improve the thermal conductivity of PCMs. The high aspect

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ratio and unique thermal properties of these nanoparticles contribute to significant enhancements in the overall thermal performance of the composite material. For instance, the thermal conductivity of MWCNTs can exceed $3000W/mK$, while a single layer of graphene can reach thermal conductivities as high as $5350W/mK$. These values are considerably higher than those of conventional PCMs like paraffin, which has a thermal conductivity of about 0.305 W/mK. The inclusion of such high-conductivity nanoparticles not only improves the heat transfer rate within the PCM but also affects other thermophysical properties such as latent heat, melting/solidification time, and phase change temperature.

The enhancement of thermal conductivity through nanoparticle doping has been confirmed by various studies. For example, Mahdi and Nsofor [17] observed a significant reduction in the solidification time of Al_2O_3 enhanced PCMs, while demonstrated that the thermal behavior of CuO-paraffin nanocomposites is highly dependent on the flow rate and inlet temperature. [17] found that nanoparticle inclusion can drastically reduce the melting time of NEPCMs in a vertical single-tube heat exchanger.

Despite these advancements, the thermal behavior of NEPCMs is complex and influenced by multiple factors including the type, shape, concentration, and distribution of nanoparticles, as well as the base PCM material. Moreover, the interaction between nanoparticles and the PCM matrix can lead to non-linear effects on thermal conductivity and phase change properties [11]. For instance, while some studies have shown that increasing nanoparticle concentration enhances thermal conductivity, others have found that beyond a certain threshold, further increases can lead to a decrease in latent heat or even hinder heat transfer due to nanoparticle agglomeration. A control volume approach provides a systematic method for analyzing the energy distribution and thermal behavior of NEPCMs [10]. This approach involves dividing the PCM into discrete control volumes and applying the principles of conservation of mass, momentum, and energy to each volume. By solving the governing equations for heat transfer and fluid flow within each control volume, it is possible to predict the temperature distribution, phase change dynamics, and overall thermal performance of the NEPCM system.

In addition, one of the primary challenges in using PCMs for thermal energy storage is ensuring uniform energy distribution throughout the material. Non-uniform distribution can lead to hotspots, reduced efficiency, and material degradation. The effectiveness of PCMs can be significantly influenced by temperature gradients. Understanding how temperature differences affect energy distribution is crucial for optimizing PCM performance.

II. RELATED WORKS

Several studies have demonstrated improvements on PCM performance, for instance, [21] investigated a triplex tube filled with Al_2 O_3 and found that the solidification time was significantly reduced by increasing nanoparticle concentration. [23] observed that NEPCM behavior is largely influenced by flow rate and inlet temperature in a triangular tube filled with CuO-paraffin nanocomposites. Similar findings have been reported by [3, 18, 31] who noted that the amount and distribution of nanomaterials play a crucial role in enhancing thermal conductivity.

However, the benefits of nanoparticle inclusion in PCMs extend beyond just thermal conductivity enhancement. For example, [33] found that the distribution of nanomaterials is as important as their thermal conductivity. [2] highlighted that agglomeration of nanoparticles can create a conductive network that enhances thermal conductivity, while [24, 7] demonstrated the importance of surfactants in improving nanoparticle dispersion and preventing cluster formation, though excessive surfactant can reduce thermal conductivity.

Research also indicates that the inclusion of nanoparticles can improve PCM's latent heat capacity without causing chemical reactions. For example, [25] observed significant increases in thermal conductivity when adding silver nanoparticles to organic ester, with no new substances being created. However, the thermal conductivity and latent heat enhancement are not consistent across all studies. Some researcher like those by [30, 2] report that thermal conductivity increases only around the phase transition temperature and decreases as the temperature exceeds the melting point. This variability highlights the complexity of nanoparticle-PCM interactions and underscores the need for detailed analysis, such as control volume analysis, to fully understand and optimize the thermal behavior of nano-enhanced PCMs in thermal energy storage applications. The control volume approach allows for a more precise examination of energy distribution and thermal dynamics within the PCM, considering factors such as heat conduction, phase change, and the influence of nanoparticles on these processes. This method is essential for designing more efficient thermal energy storage systems that leverage the benefits of nano-enhanced PCMs.

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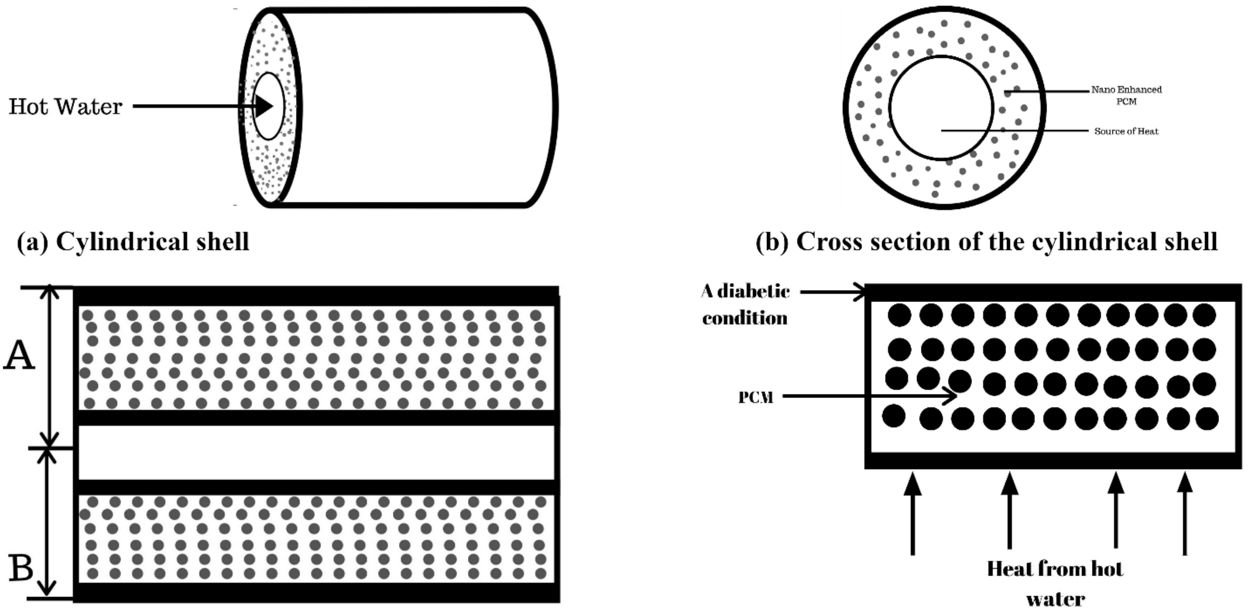
Furthermore, the shape and aspect ratio of nanoparticles are critical factors in thermal conductivity enhancement. For example, [33] found that carbon nanofibers with a higher aspect ratio significantly improved TC in erythritol. Additionally, studies by [29, 6, 16] show that nanoparticle concentration can influence both latent heat and TC, with optimal concentrations leading to better performance.

III. CONTRIBUTION

The proposed study provides significant insights into how energy is distributed within nano-enhanced PCMs under varying conditions. The analysis highlights the impact of temperature gradients and spatial positioning on the effectiveness and uniformity of energy storage, offering valuable information for optimizing PCM performance in thermal energy storage applications. While there is a substantial body of research on traditional PCMs, studies on the thermal behavior of nano-enhanced PCMs are limited. Comprehensive data is required to fully understand their potential and limitations. Applying control volume analysis to study energy distribution within PCMs provides detailed insights into the internal thermal dynamics, which are not sufficiently covered in existing literature.

IV. PROPOSED METHOD

This study employs a control volume approach to simulate the thermal behavior of Nano-Enhanced Phase Change Materials (NEPCMs) within an annular enclosure formed by two concentric horizontal cylinders. The inner cylinder wall is subjected to a constant heat flux of 225 °C, marginally above the PCM melting point, while the outer wall and vertical boundaries are adiabatic. The melt enters at a velocity of 0.003 cm/s. A representative 2D cross-section of dimensions 10 cm × 1 cm is used, as shown in Fig. 1.



(a) Cylindrical shell

(b) Cross section of the cylindrical shell

(c) Cross section of the cylindrical shell

(d) Half cross section of the cylindrical shell

Fig. 1: Cross-sectional cavity used to model the phase change process

A. Governing Equations

The fluid domain is governed by conservation of mass, momentum, and energy. Under the assumption of incompressible laminar flow and thermal equilibrium between nanoparticles and base fluid, the following equations apply:

Continuity Equation (Mass Conservation):

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

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Momentum Equations:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\beta\rho g(T-T_r) \tag{3}$$

Energy Equation:

$$\frac{\partial(\rho H)}{\partial t}+\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

B. Finite Volume Discretization

The domain is discretized into control volumes (Fig. 2), and governing equations are transformed into algebraic form using the Finite Volume Method (FVM).

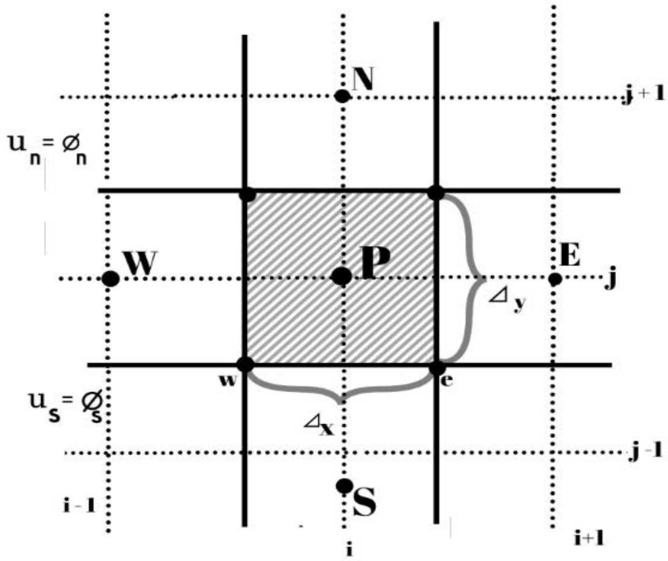

Fig. 2: 2D control volume for discretization

C. Non-Dimensionalization and Energy Equation Formulation

Using characteristic quantities (L, U_∞, ΔT), the non-dimensional form of the energy equation is expressed as:

$$\frac{1}{\Delta T}\frac{\partial(\rho H)}{\partial t^*}+\rho c_p\left(u^*\frac{\partial T^*}{\partial x^*}+v^*\frac{\partial T^*}{\partial y^*}\right)=\frac{k}{U_\infty}\left(\frac{\partial^2 T^*}{\partial x^{*2}}+\frac{\partial^2 T^*}{\partial y^{*2}}\right) \tag{5}$$

Discretizing this yields the full finite volume energy balance in dimensionless form:

$$\begin{aligned} S(H_{k+1}-H_k) \quad &+0.5A\rho c_p u_i(T_{i+1}-T_{i-1})+0.5B\rho c_p v_j(T_{j+1}-T_{j-1}) \\ &=\frac{k_{nf}}{U_\infty}\left[Q(T_{i+1}-2T_i+T_{i-1})+R'(T_{j+1}-2T_j+T_{j-1})\right] \end{aligned} \tag{6}$$

where $S=\frac{\Delta x\Delta y}{\Delta T}$, $A=\Delta y\Delta t$, $B=\Delta x\Delta t$, $Q=\frac{\Delta y\Delta t}{\Delta x}$, $R'=\frac{\Delta x\Delta t}{\Delta y}$, H is the enthalpy, T is the temperature, u, v are velocities in x and y. The thermal conductivity and dynamic viscosity of NEPCM are computed using Maxwell and Brinkman models respectively:

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$$k_{nf} = k_{PCM} \cdot \frac{k_p + 2k_{PCM} - 2\phi(k_{PCM} - k_p)}{k_p + 2k_{PCM} + \phi(k_{PCM} - k_p)} \quad (7)$$

$$\mu_{nf} = \frac{\mu_{PCM}}{(1-\phi)^{2.5}} \quad (8)$$

and

$$\rho_{nf} = (1-\phi)\rho_{PCM} + \phi\rho_p \quad (9)$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_{PCM} + \phi(\rho c_p)_p \quad (10)$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_{PCM} + \phi(\rho\beta)_p \quad (11)$$

$$(\rho L)_{nf} = (1-\phi)(\rho L)_{PCM} \quad (12)$$

D. Enthalpy-Temperature Relation for PCM

The enthalpy of the PCM is defined as:

$$H = c_p(T - T_r) + f_l L \quad (13)$$

The liquid fraction f_l is evaluated using:

$$f_l = \begin{cases} 0, & H \leq H_s \\ \frac{H - H_s}{H_l - H_s}, & H_s < H < H_l \\ 1, & H \geq H_l \end{cases} \quad (14)$$

V. RESULTS

A. Parameter estimation

The numerical simulations depends on the following parameters estimated in TABLE I.

TABLE I: PARAMETER ESTIMATION (ESTIMATION IS BASED ON ALUMINUM OXIDE (Al_2O_2))

Parameter	Description	Value range	Value used	Value Computed	Units	Source
ρ_p	Density of Al_2O_2	$4 - 4.95$	4.5		3*g/cm^3	[19]
2*ρ_{PCM}	Density of $NaNO_3$	2.26	-	2*2.17		[15]
	Density of KNO_3	2.11				[17]
Cp	Heat capacity of Al_2O_2	$0.849 - 0.9$	0.88	-	3*J/K	[5]
2*Cp_{PCM}	Heat capacity of $NaNO_3$	$0.072 - 0.298$	0.129	2*0.137		[4]
	Heat capacity of KNO_3	0.142	-			[14]
β_p	Coefficient of Thermal expansion volume of Al_2O_2	75×10^{-6}	-	75×10^{-6}	3*$/K$	[26]
2*β_{PCM}	Coefficient of Thermal expansion volume of $NaNO_3$	83×10^{-6}	-	2*57.2		[9]
	Coefficient of Thermal expansion volume of KNO_3	$30 - 100 \times 10^{-6}$	40			[12]
k_p	Thermal conductivity of Al_2O_2	237	-	-	3*W/mK	[32]
2*k_{PCM}	Thermal conductivity of $NaNO_3$	$0.5 - 0.512$	0.512	2*0.58		[20]
	Thermal conductivity of KNO_3	0.62	-			[27]

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B. Numerical simulation

We use the Fig. 2 and with (6) to analyze control volume on energy distribution on thermal behavior of nano-enhanced PCMs in thermal energy storage.

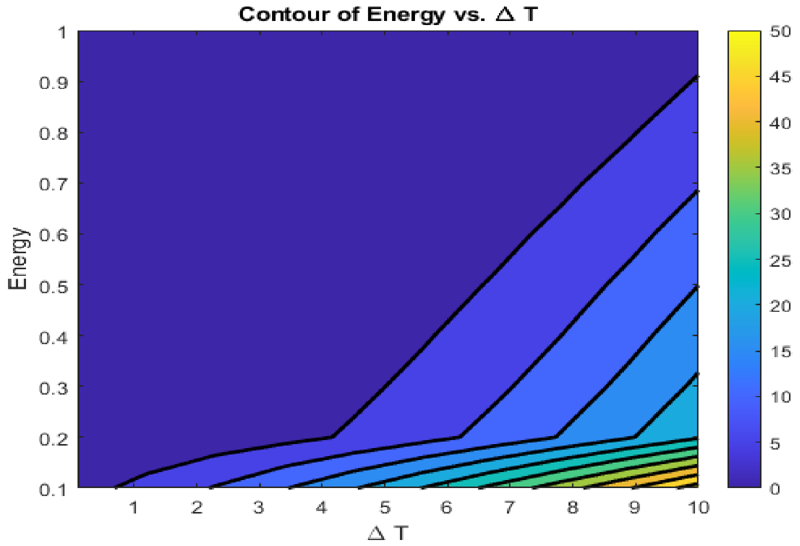

Fig. 3: Contour of Energy vs. ΔT (Temperature Difference)

Fig.3 indicate how energy distribution changes with varying temperature differences. The gradient suggests that as the temperature difference increases, the energy distribution becomes more concentrated, particularly at higher ΔT values. This implies that the PCM is more effective at storing energy at higher temperature differences, where more energy can be stored due to the higher driving temperature gradient.

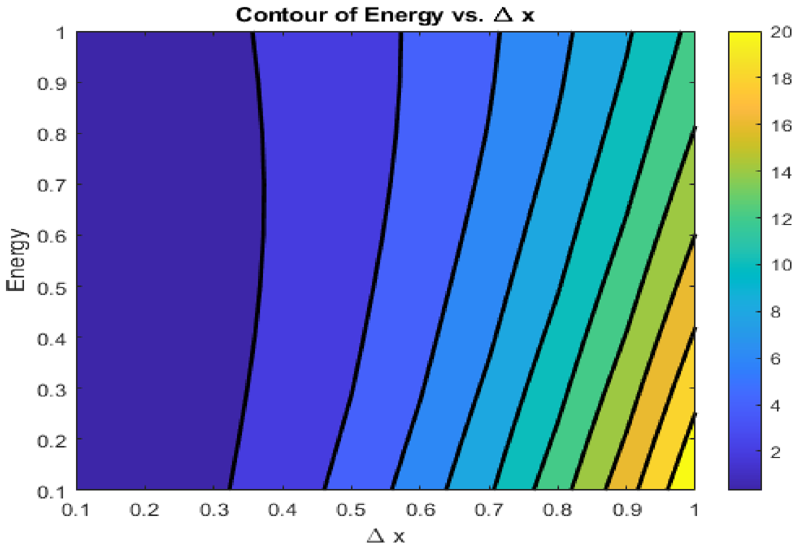

Fig. 4: Contour of Energy vs. ΔT (Temperature Difference)

Fig. 4 show how energy distribution varies along the spatial dimension (X-direction). Energy distribution seems more uniform across smaller Δx values, but as you move towards higher Δx, there's a sharper gradient in the energy distribution. This indicates that energy distribution within the PCM is more uniform closer to the heat source or within the central region of the material, while further away (at larger Δx), energy distribution becomes less uniform, possibly due to heat losses or non-uniform thermal conductivity.

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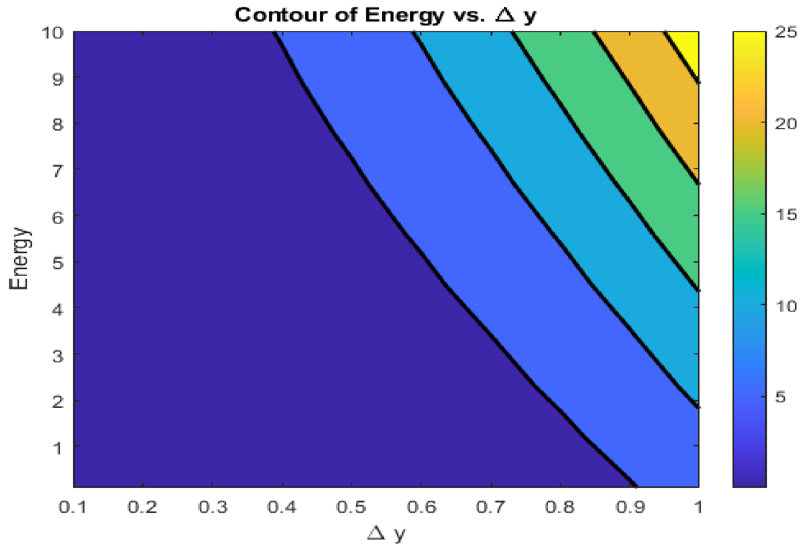

Fig. 5: Contour of Energy vs. ΔT (Temperature Difference)

Fig. 5 shows lines representing energy distribution along the Y-direction. Energy distribution is more uniform at smaller Δy values, while it becomes more variable as Δy increases. Similar to the Δx plot, this suggests that energy distribution is affected by the spatial positioning within the PCM, potentially indicating directional dependence of thermal conductivity or the influence of boundary conditions.

Fig. 3- Fig. 5 contour plots collectively demonstrate how energy is distributed within nano-enhanced PCMs under different conditions. The variation along temperature difference (ΔT) and spatial dimensions (Δx and Δy) offers insights into how these materials behave in thermal energy storage applications. Specifically, the analysis points to a significant impact of temperature gradients and spatial positioning on the effectiveness and uniformity of energy storage within these materials, which is crucial for optimizing their performance in practical applications.

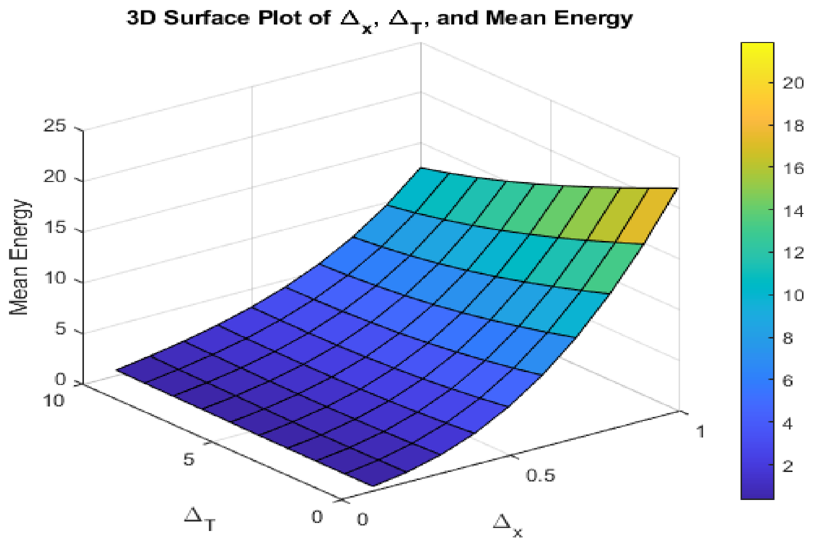

Fig. 6: 3D Surface Plot of Δ_x, Δ_T, and Mean Energy

Fig. 6 plot shows how the mean energy varies with changes in spatial distance (Δ_x) and temperature difference (Δ_T). As Δ_x and Δ_T increase, the mean energy also increases, indicating a direct relationship. The curvature suggests nonlinear behavior, with energy distribution becoming more significant at higher values of Δ_x and Δ_T. The plot can indicate how thermal energy is distributed within the PCM as it undergoes phase change, influenced by the spatial distance and temperature gradient. Higher mean energy at larger Δ_x and Δ_T may imply more effective thermal energy storage or transfer in those regions.

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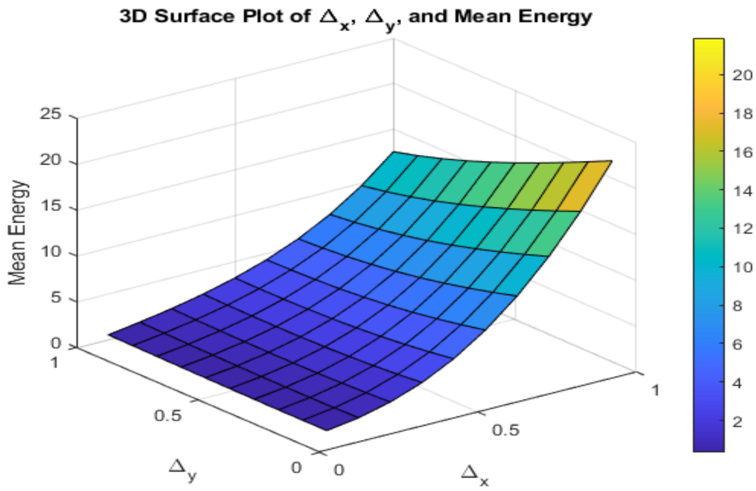

Fig. 7: 3D Surface Plot of Δ_x, Δ_y, and Mean Energy

Fig. 7 plot show how mean energy varies with changes in spatial distances (Δ_x and Δ_y). Similar to Figure 6, as Δ_x and Δ_y increase, the mean energy increases. The surface suggests a symmetrical energy distribution with respect to Δ_x and Δ_y. This plot provides insight into the spatial uniformity of energy distribution within the PCM. Higher energy values at larger Δ_x and Δ_y suggest that energy is being stored effectively across the material.

Fig. 6 - Fig. 7 plots collectively illustrate how mean energy distribution within nano-enhanced PCMs is influenced by spatial variations and thermal gradients. From a fluid dynamics standpoint, these visualizations help understand the efficiency and effectiveness of energy storage in the materials. It can be included that:

- Mean energy increases with larger spatial and thermal variations.
- Energy distribution appears symmetrical with respect to spatial parameters.
- The nonlinear nature of the plots suggests complex interactions within the PCM during phase transitions.

VI. CONCLUSION

The growing global energy demand and the need for sustainable energy solutions have driven research into effective energy storage technologies, with TES emerging as a promising approach. Among TES technologies, PCMs are particularly notable for their high energy storage density and consistent energy release during phase transitions. However, their low thermal conductivity poses significant challenges, limiting the efficiency of heat transfer within the material. This study investigates the enhancement of thermal conductivity in PCMs through the incorporation of nanoparticles, creating NEPCMs. The methodology involves applying a control volume approach to analyze energy distribution and thermal behaviour within NEPCMs under varying conditions, with a focus on temperature gradients and spatial positioning. The results reveal that nanoparticle inclusion significantly enhances the thermal conductivity and overall performance of PCMs. Energy distribution becomes more concentrated at higher temperature differences, and spatial uniformity is observed in regions closer to the heat source, with nonlinear behaviour indicating complex interactions during phase transitions. The findings underscore the importance of considering temperature gradients and spatial positioning in the design of NEPCMs. Future research should explore the long-term stability of NEPCMs and the effects of varying nanoparticle types and concentrations to harness their potential fully in energy storage systems.

REFERENCES

[1] Waseem Aftab, Ali Usman, Jinming Shi, Kunjie Yuan, Mulin Qin, and Ruqiang Zou. Phase change material-integrated latent heat storage systems for sustainable energy solutions. *Energy & Environmental Science*, 14(8):4268–4291, 2021.

[2] Yanbin Cui, Caihong Liu, Shan Hu, and Xun Yu. The experimental exploration of carbon nanofiber and carbon nanotube additives on thermal behavior of phase change materials. *Solar Energy Materials and Solar Cells*, 95(4):1208–1212, 2011.

[3] Nitesh Das, Yasuyuki Takata, Masamichi Kohno, and Sivasankaran Harish. Melting of graphene based phase change nanocomposites in vertical latent heat thermal energy storage unit. *Applied Thermal Engineering*, 107:101–113, 2016.

[4] Octav Enea, Prem Paul Singh, Earl M Woolley, Keith G McCurdy, and Loren G Hepler. Heat capacities of aqueous nitric acid, sodium nitrate, and potassium nitrate at 298.15 k: δcpo of ionization of water. *The Journal of Chemical Thermodynamics*, 9(8):731–734, 1977.

[5] TK Engel. The heat capacities of al2o3, uo2 and puo2 from 300 to 1100 k. *Journal of Nuclear Materials*, 31(2):211–214, 1969.

[6] Ali Fallahi, Gert Guldentops, Mingjiang Tao, Sergio Granados-Focil, and Steven Van Dessel. Review on solid-solid phase change materials for thermal energy storage: Molecular structure and thermal properties. *Applied Thermal Engineering*, 127:1427–1441, 2017.

[7] Yong Yang Gan, Hwai Chyuan Ong, Tau Chuan Ling, Nurin Wahidah Mohd Zulkifli, Chin-Tsan Wang, and Yung-Chin Yang. Thermal conductivity optimization and entropy generation analysis of titanium dioxide nanofluid in evacuated tube solar collector. *Applied Thermal Engineering*, 145:155–164, 2018.

[8] Yong Hu and Changfa Guo. Carbon nanotubes and carbon nanotubes/metal oxide heterostructures: synthesis, characterization and electrochemical property. *Carbon Nanotubes-Growth and Applications*, 2011.

[9] M Md Ibrahim, V Ramachandran, K Sarangapani, and R Srinivasan. Thermal expansion of sodium nitrate (i). *Journal of Physics and Chemistry of Solids*, 47(5):517–520, 1986.

[10] MAM Irwan, CS Nor Azwadi, Y Asako, and J Ghaderian. Review on numerical simulations for nano-enhanced phase change material (nepcm) phase change process. *Journal of Thermal Analysis and Calorimetry*, 141:669–684, 2020.

[11] B Eanest Jebasingh and A Valan Arasu. A comprehensive review on latent heat and thermal conductivity of nanoparticle dispersed phase change material for low-temperature applications. *Energy Storage Materials*, 24:52–74, 2020.

[12] Mengting Ji, Laiquan Lv, Jingwen Liu, Yan Rong, and Hao Zhou. Nano3-kno3/eg/al2o3 shape-stable phase change materials for thermal energy storage over a wide temperature range: Sintering temperature study. *Solar Energy*, 258:325–338, 2023.

[13] Hussam Jouhara, Alina Żabnieńska-Góra, Navid Khordehgah, Darem Ahmad, and Tom Lipinski. Latent thermal energy storage technologies and applications: A review. *International Journal of Thermofluids*, 5:100039, 2020.

[14] M Kawakami, K Suzuki, S Yokoyama, and T Takenaka. Heat capacity measurement of molten nano3-nano2-kno3 by drop calorimetry. In *VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy*, pages 201–208, 2004.

[15] Mark A Kedzierski. Viscosity and density of aluminum oxide nanolubricant. *international journal of refrigeration*, 36(4):1333–1340, 2013.

[16] Sedat Keleş, Kamil Kaygusuz, and Ahmet Sarı. Lauric and myristic acids eutectic mixture as phase change material for low-temperature heating applications. *International Journal of Energy Research*, 29(9):857–870, 2005.

[17] Wolfgang Laue, Michael Thiemann, Erich Scheibler, and Karl Wilhelm Wiegand. Nitrates and nitrites. *Ullmann's Encyclopedia of Industrial Chemistry*, 2000.

[18] Saw C Lin and Hussain H Al-Kayiem. Evaluation of copper nanoparticles–paraffin wax compositions for solar thermal energy storage. *Solar Energy*, 132:267–278, 2016.

[19] Maoyuan Liu, Patrick Masset, and Angus Gray-Weale. Solubility of sodium in sodium chloride: a density functional theory molecular dynamics study. *Journal of The Electrochemical Society*, 161(8):E3042, 2014.

[20] Ruguang Li, Jiaoqun Zhu, Weibing Zhou, Xiaomin Cheng, and Yuanyuan Li. Thermal properties of sodium nitrate-expanded vermiculite form-stable composite phase change materials. *Materials & design*, 104:190–196, 2016.

[21] Jasim M Mahdi and Emmanuel C Nsofor. Solidification of a pcm with nanoparticles in triplex-tube thermal energy storage system. *Applied Thermal Engineering*, 108:596–604, 2016.

ISSN 2350-1049

International Journal of Recent Research in Interdisciplinary Sciences (IJRRIS)
Vol. 12, Issue 2, pp: (1-10), Month: April - June 2025, Available at: www.paperpublications.org

[22] Shadpour Mallakpour and Elham Khadem. Carbon nanotube–metal oxide nanocomposites: Fabrication, properties and applications. *Chemical Engineering Journal*, 302:344–367, 2016.

[23] ZN Meng and P Zhang. Experimental and numerical investigation of a tube-in-tank latent thermal energy storage unit using composite pcm. *Applied Energy*, 190:524–539, 2017.

[24] Zhou Mingzheng, Xia Guodong, Li Jian, Chai Lei, and Zhou Lijun. Analysis of factors influencing thermal conductivity and viscosity in different kinds of surfactant solutions. *Experimental Thermal and Fluid Science*, 36:22–29, 2012.

[25] R Parameshwaran, R Jayavel, and S Kalaiselvam. Study on thermal properties of organic ester phase-change material embedded with silver nanoparticles. *Journal of thermal analysis and calorimetry*, 114:845–858, 2013.

[26] Hsin-Yi Peng, Yi-An Wei, Kao-Chi Lin, Shen-Fu Hsu, Jyh-Chern Chen, Chin-Pao Cheng, and Chan-Shan Yang. Terahertz characterization of functional composite material based on abs mixed with ceramic powder. *Optical Materials Express*, 13(9):2622–2632, 2023.

[27] Melina Roshandell. *Thermal Conductivity Enhancement of High Temperature Phase Change Materials for Concentrating Solar Power Plant Applications*. PhD thesis, UC Riverside, 2013.

[28] Enas Taha Sayed, Abdul Ghani Olabi, Abdul Hai Alami, Ali Radwan, Ayman Mdallal, Ahmed Rezk, and Mohammad Ali Abdelkareem. Renewable energy and energy storage systems. *Energies*, 16(3):1415, 2023.

[29] Jifen Wang, Huaqing Xie, Zhixiong Guo, Lihui Guan, and Yang Li. Improved thermal properties of paraffin wax by the addition of tio2 nanoparticles. *Applied Thermal Engineering*, 73(2):1541–1547, 2014.

[30] Jifen Wang, Huaqing Xie, and Zhong Xin. Thermal properties of paraffin based composites containing multi-walled carbon nanotubes. *Thermochimica Acta*, 488(1-2):39–42, 2009.

[31] Weilong Wang, Xiaoxi Yang, Yutang Fang, Jing Ding, and Jinyue Yan. Enhanced thermal conductivity and thermal performance of form-stable composite phase change materials by using β-aluminum nitride. *Applied Energy*, 86(7-8):1196–1200, 2009.

[32] Ailing Zhang and Yanxiang Li. Thermal conductivity of aluminum alloysâ€"a review. *Materials*, 16(8):2972, 2023.

[33] Qiang Zhang, Zhiling Luo, Qilin Guo, and Gaohui Wu. Preparation and thermal properties of short carbon fibers/erythritol phase change materials. *Energy conversion and management*, 136:220–228, 2017.