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Heat Transfer-Based on Nano-particles for Thermal Energy Storage in Phase Change Material

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Abstract: **This study investigates the enhancement of thermal energy storage performance in phase change materials (PCMs) through the integration of nanoparticles, focusing on nano-enhanced PCMs (NEPCMs). A finite volume numerical model is developed to simulate heat transfer and fluid dynamics during the melting process within a cylindrical enclosure. The governing equations of mass, momentum, and energy are discretized and non-dimensionalized to evaluate the effects of nanoparticle concentration, size, and distribution on heat transfer efficiency and thermodynamic stability. Aluminum oxide (Al_2O_3) is used as the nanoparticle additive, with simulation results highlighting the relationship between enthalpy, energy, and velocity. The results demonstrate that nanoparticle incorporation significantly improves thermal conductivity, stabilizes flow during phase transition, and enhances overall system performance. These findings offer crucial insights into the design and optimization of solar thermal energy storage systems using NEPCMs for sustainable energy applications.**

Keywords: **Heat transfer; Nanoparticle; Phase change materials; Solar thermal energy storage; Thermal energy storage.**

I. INTRODUCTION

The rising energy demands driven by population growth, industrial expansion, urbanization, and improved living standards have created significant challenges for energy consumption and management [26]. With the high costs, environmental concerns, and limited availability of conventional energy sources, there is an increasing need to focus on the efficient use of renewable energy. Among these, solar energy stands out as the most preferred due to its easy accessibility during daylight hours. However, effectively addressing the time gap between solar energy availability and consumption is crucial for maximizing the use of this abundant resource [22, 25]. The inherent imbalance between supply and demand in solar energy systems, caused by seasonal variations and the intermittent nature of sunlight, makes efficient storage and utilization essential. Solar energy must be stored during daylight hours and used during periods when sunlight is unavailable.

To optimize the use of solar energy, integrating solar thermal energy generation with a thermal energy storage (TES) system is necessary. The development of solar thermal power plants has been slow due to high costs, lower efficiency, and the fluctuating nature of solar energy. While the last two factors are beyond control, researchers continue to strive for cost optimization and higher plant efficiency [19]. TES systems can be classified into three main types: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and chemical heat thermal energy storage (CHTES). Among these, LHTES systems using phase change materials (PCMs) are particularly well-suited for solar energy storage due to their high thermal energy storage capacity per unit volume and their ability to store and release heat at a constant temperature during phase changes.

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In recent years, the focus has shifted toward enhancing the performance of PCM-based thermal energy storage systems by incorporating nanoparticles [6, 24]. The introduction of nanoparticles into PCMs can significantly improve heat transfer rates and thermal stability, addressing some of the critical challenges associated with LHTES systems [1, 8]. This area of research has become increasingly important as scientists and engineers continue to explore ways to enhance the efficiency and reliability of TES systems, making them more viable for large-scale applications. By improving the heat transfer capabilities and stability of PCM-based systems through nano-particle integration, the overall efficiency and effectiveness of solar thermal energy storage can be significantly enhanced, contributing to more sustainable energy solutions [2].

II. CONTRIBUTION

The present study enhances our understanding of the heat transfer mechanisms within PCMs when nanoparticles are introduced. The study will quantify the improvements in thermal conductivity and identify the optimal nanoparticle concentration and type that maximize heat transfer rates, as demonstrated through heat transfer enhancement visualizations. The research will offer a detailed analysis of the thermodynamic stability of nanoparticle-enhanced PCMs, particularly focusing on their behavior during repeated thermal cycles. This includes evaluating how nanoparticle dispersion affects the consistency of phase transitions and overall system stability, which will be illustrated in thermodynamic stability images.

The study characterizes the flow dynamics of nanoparticle-laden PCMs, examining the effects of nano-particle size, shape, and distribution on fluid behavior during phase transitions. This analysis will provide insights into potential challenges like nano-particle agglomeration and sedimentation, which are critical for maintaining uniform heat transfer across the PCM, as shown through flow dynamics analysis. The research seeks to optimize heat transfer efficiency in TES systems by identifying conditions under which nanoparticle-enhanced PCMs achieve the highest thermal performance while maintaining material stability. The results is reflected in heat transfer efficiency evaluations, offering design guidelines for the optimal use of nano-particles in TES systems.

The findings of the research contributes to the broader field of sustainable energy by improving the efficiency and reliability of TES systems. By enhancing the performance of PCM-based systems, particularly in solar thermal energy storage applications, the study will help make renewable energy sources more viable and efficient for large-scale use. This work bridges the gap between theoretical fluid mechanics and practical energy storage, providing valuable data and methodologies for advancing the field of thermal energy storage.

III. RELATED WORKS

In their review, [23] categorized phase change materials (PCMs) into low, middle, and high-temperature groups, assessing the advancements and limitations in each category. The review highlighted various enhancement techniques, including using nanoparticles (NPs), combinations with fins, heat pipes, and highly conductive porous materials. Both experimental and numerical studies were evaluated, revealing that NPs generally improved the thermal conductivity of PCMs, with materials like Al_2O_3, and carbon-based nano particles being the most extensively studied. Despite these advancements, the review noted a need for more research on middle and high-temperature PCMs and the combination of multiple enhancement techniques. Some studies found NPs to have minimal impact compared to other methods, where others demonstrated their significant benefits.

[3] explored the enhancement of heat transfer in PCMs through various fin arrangements and modifications to PCM geometry. The study found that fins were the most commonly used enhancement method in concentric tube heat exchangers due to their cost-effectiveness and ease of use. Modifying PCM geometry to increase surface area for heat exchange without reducing PCM mass also improved heat transfer. The research identified a cascaded system as effective for utilizing heat transfer fluid energy during charging and discharging cycles. Although metal foam materials provided a very high heat transfer rate, this came at the cost of reduced storage capacity.

[12] conducted numerical analyses on using metal oxides as potential nano-additives for paraffin in thermal storage applications. The study aimed to evaluate the technical and economic viability of metal oxide-based nano-PCMs. A numerical model incorporating natural convection and transient variations in thermophysical properties was developed and simulated for charging and discharging cycles in a shell and tube heat exchanger. The results showed that including nanoparticles increased thermal conductivity and surface area, enhancing charging and discharging rates. However, higher nanoparticle concentrations reduced natural convection, overall thermal enthalpy and increased costs.

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[2] investigated the melting process of nano-PCM in a thermal energy storage (TES) system using scale analysis, numerical simulation, and experimental analysis. The study focused on the impact of CuO nanoparticles dispersed in coconut oil PCM on heat transfer and energy storage within a square enclosure. The research demonstrated that adding nanoparticles improved the melting process, with a detailed scale analysis helping to establish relationships between key dimensionless numbers. The experimental results corroborated the numerical findings, showing significant improvements in melting performance due to the inclusion of nanoparticles.

[18] addressed the issue of decreasing electrical efficiency in photovoltaic thermal (PVT) modules due to rising cell temperatures by proposing a hybrid PVT system incorporating Phase Change Material (PCM). The study highlighted the potential of using nanoparticles to enhance the thermal conductivity of PCMs, thereby improving thermal energy storage efficiency. Carbon-based nanoparticles outperformed metal-based ones, with graphite-based nanoparticles showing significant increases in thermal conductivity. The environmental impact of using nanofluids and nano-enhanced PCMs (NEPCMs) was also considered, with carbon-based nanofluids contributing to a reduction in CO_2 emissions.

[16] examined the melting and solidification characteristics of nano-enhanced phase change materials (NEPCM) by dispersing multi-walled carbon nanotubes (MWCNTs) into paraffin without any dispersants. The study found that adding MWCNTs significantly reduced melting and solidification times, with the most significant improvements observed at higher MWCNT concentrations. The latent heat of the NEPCM also increased compared to pure paraffin, indicating enhanced thermal storage capacity.

[17] conducted an experimental study to enhance the melting performance of inorganic PCMs by mixing them with thermally conductive nano-materials. The study involved preparation of PCMs for both summer and winter conditions, with varying weight percentages of alumina and copper oxide nanopowders. The results showed that low-melting-temperature PCMs for winter conditions formed stable composites with increased viscosity as nano-material composition increased. The study recommended using 5.0 wt% nano-copper oxide in PCM sp11 for winter applications and 5.0 wt% nano-CuO in sp26 with a thickening agent for summer conditions, based on the observed melting rates and stability.

These studies collectively highlight the impact of nano-particles on heat transfer and stability in PCM-based thermal energy storage systems. Nano-particles generally enhance thermal conductivity, but the effectiveness varies depending on the type and concentration of nano-particles used. Significant heat transfer and energy storage improvements have been observed, however challenges such as reduced natural convection, increased costs, and stability issues at higher nanoparticle concentrations still remain. The continued exploration of nanoparticle-enhanced PCMs, particularly in combination with other enhancement techniques, is crucial for advancing thermal energy storage technologies.

The present study builds on the existing body of literature on nanoparticle-enhanced phase change materials (NEPCMs) by providing a more detail understanding of the heat transfer mechanisms involved when nano-particles are introduced into PCMs. The study is set to make significant contributions by quantifying the improvements in thermal conductivity, which has been a focal point in several studies, such as those by [23, 12, 2]. These previous works highlighted the role of nano-particles like Al_2O_3 and copper oxide in enhancing thermal conductivity, albeit with varying degrees of effectiveness depending on the nano-particle type and concentration. However, this study advances the field by not only quantifying these improvements but also identifying the optimal nano-particle concentration and the type that maximize heat transfer rates, as evidenced through heat transfer enhancement visualizations. Moreover, this study delves into the thermodynamic stability of NEPCMs, which is crucial for their practical application in TES systems. In addition, the study's characterization of flow dynamics within nanoparticle-laden PCMs provides a deeper understanding of how nano-particle size, shape, and distribution influence fluid behavior during phase transitions. This aspect of the research builds on the findings of [3], who explored the impact of fin arrangements and PCM geometry on heat transfer. By analyzing potential issues such as nano-particle agglomeration and sedimentation, the study contributes to the optimization of uniform heat transfer across the PCM, a factor that is essential for the efficiency and stability of TES systems.

The study's focus on optimizing heat transfer efficiency in TES systems by identifying the conditions under which NEPCMs achieve the highest thermal performance, while maintaining material stability, is a crucial contribution. The study provides design guidelines for the optimal use of nano-particles in TES systems, thereby bridging the gap between theoretical fluid mechanics and practical energy storage applications. This aligns with the broader goals of sustainable energy by improving the efficiency and reliability of TES systems, particularly in solar thermal energy storage applications. As highlighted in

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the work of [18], enhancing the performance of PCM-based systems is vital for making renewable energy sources more viable and efficient for large-scale use. The current study makes a significant contribution to the field of thermal energy storage by advancing the understanding of the heat transfer mechanisms in NEPCMs, optimizing their performance, and ensuring their stability during thermal cycles. The findings provide valuable data and methodologies that will be instrumental in the design and development of more efficient and reliable TES systems, thereby supporting the broader transition to sustainable energy sources.

IV. PROPOSED METHOD

The PCM is enclosed within annular cavity formed between two concentric horizontal cylindrical shells with the inner shell considered to be of a significantly thinned wall subjected to a constant heat flux of 225 ^{0}C (1 ^{0}C higher than the melting point of the PCM) on the southern wall keeping the outer shell (northern wall) at adiabatic condition which simulates the PCM storing thermal energy during charging. The inlet velocity u of the melt is $0.003 cm/s$. The western and eastern walls are also kept at adiabatic condition. The elementary cross-sectional cavity of dimension 10cm (x direction) by 1cm (y direction) is used to model the phase change process as represented by the Fig. 1.

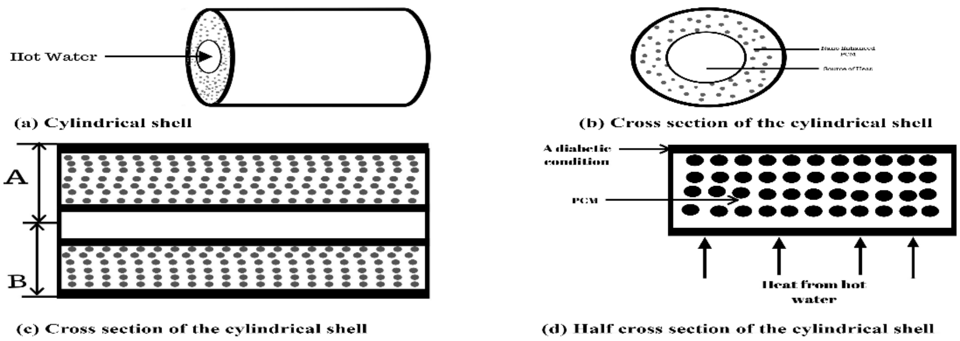

Fig. 1: Cross-sectional cavity used to model the phase change process

A. Governing Equations and Numerical Methodology

a. Conservation of Mass

The general conservation of mass for a compressible fluid is given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (1)$$

For incompressible flow, where ρ is constant, this reduces to:

$$\nabla \cdot \vec{V} = 0 \quad (2)$$

In two-dimensional form, this becomes:

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \quad (3)$$

The discretized form over a control volume yields:

$$\Delta y^*(u^*_{i+1} - u^*_{i-1}) + \Delta x^*(v^*_{j+1} - v^*_{j-1}) = 0 \quad (4)$$

b. Momentum Equations

The momentum conservation in the x-direction simplifies to:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (5)$$

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Non-dimensionalizing using characteristic scales, the equation becomes:

$$\frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{1}{Re}\left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right) \tag{6}$$

The discretized form is:

$$C[u_{k+1} - u_k] + 0.5A\bar{u}_i(u_{i+1} - u_{i-1}) + 0.5B\bar{v}_j(u_{j+1} - u_{j-1})$$
$$-\frac{\mu_{nf}}{\rho_{nf} L U_\infty}\{Q(u_{i+1} - 2u_i + u_{i-1}) + R'(u_{j+1} - 2u_j + u_{j-1})\} = 0 \tag{7}$$

where

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

The y-momentum equation in non-dimensional form is:

$$\frac{\partial v^*}{\partial t^*} + u^* \frac{\partial v^*}{\partial x^*} + v^* \frac{\partial v^*}{\partial y^*} = \frac{1}{Re}\left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}}\right) + \frac{L}{U_\infty^2}\beta g(T^*\Delta T + T_\infty - T_r) \tag{9}$$

The discretized form is:

$$C[v_{k+1} - v_k] + 0.5Au_i(v_{i+1} - v_{i-1}) + 0.5Bv_j(v_{j+1} - v_{j-1})$$
$$= \frac{1}{Re}\{Q(v_{i+1} - 2v_i + v_{i-1}) + R'(v_{j+1} - 2v_j + v_{j-1})\} + D\frac{L}{U_\infty^2}\beta g((T\Delta T + T_\infty) - T_r) \tag{10}$$

c. Energy Equation

The enthalpy-based energy equation is:

$$H = C_p(T - T_r) + f_l L \tag{11}$$

The non-dimensional energy equation is:

$$\frac{1}{\Delta T}\frac{\partial(\rho H)}{\partial t^*} + \rho C_p\left(u^* \frac{\partial T^*}{\partial x^*} + v^* \frac{\partial T^*}{\partial y^*}\right) = \frac{k}{U_\infty}\left(\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial y^{*2}}\right) \tag{12}$$

Discretized form:

$$S(H_{k+1} - H_k) + 0.5A\rho C_p u_i(T_{i+1} - T_{i-1}) + 0.5B\rho C_p v_j(T_{j+1} - T_{j-1})$$
$$= \frac{k_{nf}}{U_\infty}\{Q(T_{i+1} - 2T_i + T_{i-1}) + R'(T_{j+1} - 2T_j + T_{j-1})\} \tag{13}$$

where thermal conductivity is computed as:

$$k_{nf} = k_{PCM}\frac{k_p + 2k_{PCM} - 2(k_{PCM} - k_p)\phi}{k_p + 2k_{PCM} + (k_{PCM} - k_p)\phi} \tag{14}$$

$$S(H_{k+1} - H_k) + 0.5A\rho(C_p)u_i(T_{(i+1)} - T_{(i-1)}) + 0.5B\rho(C_p)v_j(T_{(j+1)} - T_{(j-1)})$$
$$= \frac{k_{nf}}{U_\infty}\{Q(T_{i+1} - 2T_i + T_{i-1}) + R'(T_{j+1} - 2T_j + T_{j-1})\} \tag{15}$$

The thermal conductivity of NEPCM is calculated according to the Maxwell model as

$$k_{nf} = k_{PCM}\frac{k_p + 2k_{PCM} - 2(k_{PCM} - k_p)\phi}{k_p + 2k_{PCM} + (k_{PCM} - k_p)\phi} \tag{16}$$

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where k_{PCM}, k_p, and k_{nf} are thermal conductivities of pure PCMs, nanoparticles and NEPCMs respectively. The density of nanofluid ρ_{nf} is calculated as

$$\rho_{nf} = (1-\phi)\rho_{PCM} + \phi\rho_p \tag{17}$$

where ρ_{PCM}, and ρ_p are densities of pure PCM and nanoparticles. The heat capacitance of NEPCMs $(\rho c_p)_{nf}$ is defined as

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_{PCM} + \phi(\rho c_p)_p \tag{18}$$

where $(\rho c_p)_{PCM}$ is the heat capacitance of the PCM, and $(\rho c_p)_p$ is the heat capacitance of nanoparticles. Thermal expansion volume of NEPCMs $(\rho\beta)_{nf}$ is given as

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_{PCM} + \phi(\rho\beta)_p \tag{19}$$

where $(\rho\beta)_{PCM}$ and $(\rho\beta)_p$ are thermal expansion volume of pure PCM and nanoparticles, respectively. The latent heat of NEPCMs is computed as

$$(\rho L)_{nf} = (1-\phi)(\rho L)_{PCM} \tag{20}$$

where $(\rho L)_{PCM}$ is the latent heat of pure PCM. Then the coresponding enthalpy of NEPCM H_{nf} is given as

$$H_{nf} = Cp_{nf}(T - T_r) + f_l L_{nf} \tag{21}$$

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) AS NANO PARTICLES) AND PCM

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	[14]
2*ρ_{PCM}	Density of $NaNO_3$	2.26	-	2*2.17		[11]
	Density of KNO_3	2.11				[13]
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	-			[10]
β_p	Coefficient of Thermal expansion volume of Al_2O_2	75×10^{-6}	-	75×10^{-6}	3*$/K$	[20]
2*β_{PCM}	Coefficient of Thermal expansion volume of $NaNO_3$	83×10^{-6}	-	2*57.2		[7]
	Coefficient of Thermal expansion volume of KNO_3	$30-100\times10^{-6}$	40			[9]
k_p	Thermal conductivity of Al_2O_2	237	-	-	3*W/mK	[27]
2*k_{PCM}	Thermal conductivity of $NaNO_3$	$0.5-0.512$	0.512	2*0.58		[15]
	Thermal conductivity of KNO_3	0.62	-			[21]

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B. Numerical simulation

The numerical simulation results focuses on illustrating how the addition of nano-particles may influence the relationship between stored thermal energy and enthalpy, potentially enhancing the heat storage capacity of the PCM.

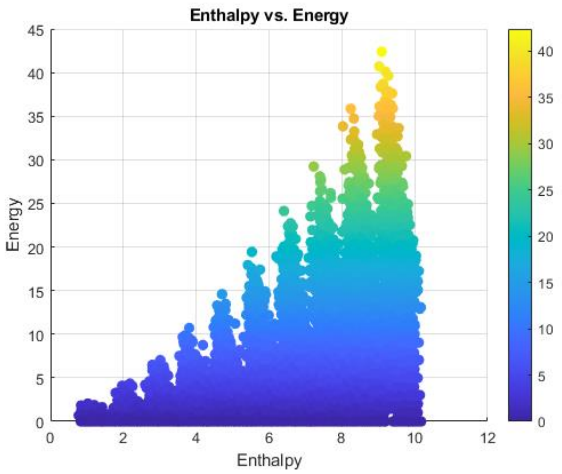

Fig. 2: Scatter Plot of energy against enthalpy

Fig. 2 shows a direct relationship between enthalpy and energy, where increasing enthalpy corresponds to higher energy values. This relationship is consistent with the thermodynamic principles, where enthalpy is a measure of the total heat content in the system, and energy is a reflection of the stored thermal energy within the PCM. The figure indicates that the importance of introduction of nanoparticles into PCM, which can significantly influence the heat transfer characteristics by enhancing the thermal conductivity. The concentration of data points, particularly at higher energy levels, suggests that the incorporation of nanoparticles has led to a more efficient heat transfer process, allowing the PCM to reach higher energy states as enthalpy increases. The color gradient shows that this efficiency is not uniform across all conditions, with some configurations achieving better performance (indicated by the transition from blue to yellow). The dispersion of data points, especially as they become more spread out at higher energy and enthalpy levels, could indicate the challenges in maintaining stability within the PCM when nanoparticles are introduced. Issues like nanoparticle agglomeration and sedimentation can affect how uniformly heat is transferred and stored in the PCM, leading to variations in performance as depicted in the plot. The plot may also be illustrating the impact of repeated thermal cycling, where the consistency of phase transitions and the overall stability of the NEPCM system are critical. A stable system would show a more uniform and predictable relationship between enthalpy and energy across the range of conditions tested.

The simulation also focused on finding a relationship between energy, enthalpy, and velocity. The results is presented in Fig. 3.

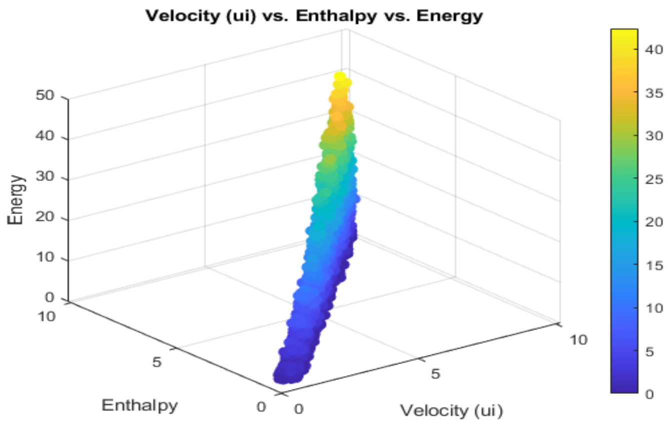

Fig. 3: A 3D plot of velocity enthalpy and energy.

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Fig. 3 indicated that the inclusion of velocity as a parameter provides insight into the fluid dynamics within the PCM system. Velocity refers to the speed at which the nanoparticle-enhanced PCM flows or moves during phase transitions. The narrow, linear distribution of data points suggests a strong correlation between velocity, enthalpy, and energy. As velocity increases, both enthalpy and energy also increase, indicating that higher fluid motion enhances heat transfer efficiency. This is consistent with the behavior expected in systems where nano-particles are introduced to improve thermal conductivity and heat transfer rates. The introduction of nanoparticles is expected to alter the flow dynamics of the PCM. The plot illustrates how these changes in velocity affect the overall thermal performance (enthalpy and energy). Nanoparticles can disrupt the natural convection currents within the PCM, either enhancing or hindering the uniformity of heat distribution depending on their concentration, size, and dispersion. The linear pattern observed in the plot may indicate that the nanoparticle concentration used in this scenario optimizes the fluid's velocity, leading to improved energy absorption and storage (higher enthalpy and energy values). This alignment also suggests that the flow remains stable and consistent across different velocities, which is crucial for maintaining uniform heat transfer. The consistent gradient in the color mapping, from blue to yellow, along the line of data points suggests that the system maintains its stability while increasing velocity. This is essential for TES systems, as stability in thermal performance across different velocities ensures reliable and predictable energy storage and release cycles. If nanoparticles are not uniformly dispersed or if their concentration is too high, issues like agglomeration could arise, leading to inconsistent flow patterns and, consequently, uneven heat distribution. The smooth transition in the plot indicates that such issues may be minimized in the studied configuration, contributing to the stability of the PCM-based TES system.

The simulation also focused on finding a relationship between energy and velocity. The results is presented in Fig. 4.

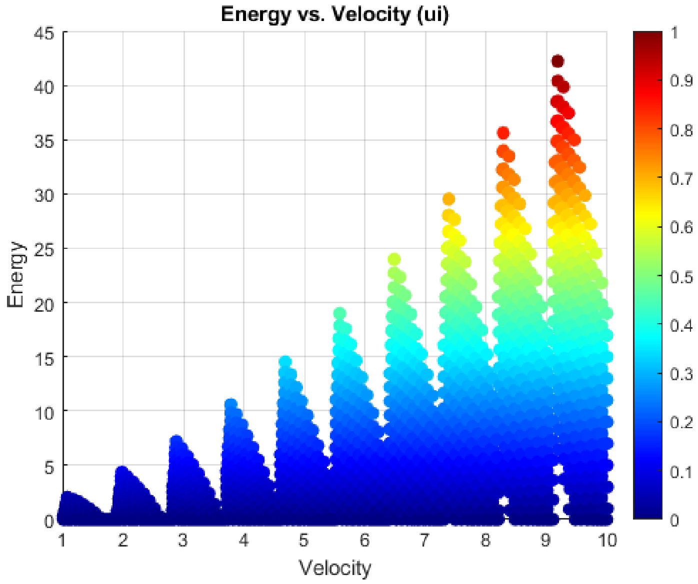

Fig. 4: A plot of energy against velocity.

Fig. 4 plot shows distinct clusters of data points that form bands along the energy axis, with these bands becoming narrower and more dispersed as velocity increases. At low velocities (1-3 units), energy levels remain low, indicating limited heat transfer or energy absorption by the PCM. As velocity increases (especially beyond 7 units), the energy levels rise significantly, reaching values above 40 units. This suggests that higher velocities enhance the heat transfer process within the PCM, likely due to improved fluid motion and mixing, which facilitates better heat distribution. The observed trend aligns with the expected impact of nanoparticles on heat transfer. Nanoparticles can increase the thermal conductivity of PCMs, improving the system's ability to absorb and store energy as velocity increases. The enhanced heat transfer efficiency at higher velocities could be attributed to the presence of nanoparticles that enable faster and more uniform thermal energy distribution throughout the PCM. The color gradient, shifting from blue to red, indicates that as velocity and energy increase, the system reaches higher levels of thermal performance (closer to 1 in the color scale). This further confirms the positive impact of velocity on the overall efficiency of the PCM system when nanoparticles are introduced. The clustering and formation of distinct bands in the plot suggest that there may be specific velocity ranges where the system exhibits stable energy absorption behavior. For instance, around velocities of 7-9 units, there is a noticeable increase in energy levels with a corresponding shift in color from blue to yellow, indicating an optimal operating range for the system. The presence of stable energy bands at different velocities may indicate that the PCM, with nano-particle enhancement, maintains a stable phase change process across these velocities. This stability is crucial for the long-term reliability of TES systems, ensuring consistent performance over repeated thermal cycles.

VI. CONCLUSION

The numerical investigation conducted in this study highlights the effectiveness of nano-enhanced phase change materials (NEPCMs) in improving the thermal performance of latent heat thermal energy storage (LHTES) systems. Through detailed simulations and parametric analysis, the incorporation of nanoparticles into PCMs has been shown to significantly enhance thermal conductivity, reduce thermal response time, and improve phase change stability. The analysis also confirms a strong correlation between enthalpy, velocity, and energy, suggesting that optimal nanoparticle concentrations not only boost heat transfer but also contribute to more uniform and stable thermal profiles during repeated thermal cycles.

The results further demonstrate that the fluid dynamics of NEPCMs can be tailored by adjusting the nanoparticle size and dispersion, minimizing issues such as agglomeration and sedimentation. The model developed provides a robust framework for designing advanced TES systems with optimized heat transfer properties. Ultimately, the insights from this study contribute to the growing body of knowledge in renewable energy systems, paving the way for more efficient, scalable, and sustainable thermal energy storage solutions, particularly for solar applications.

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