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Enhanced thermal cycling in multi PCM energy storage using advanced semi cylindrical fin configurations

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ABSTRACT

This study numerically investigates the charging and discharging behavior of multi-phase change materials (m-PCMs) enhanced in a semi-cylindrical enclosure equipped with rectangular and triangular fins. Organic (H395, H380, H355) and inorganic (PCM-S, PCM-M, PCM-C) PCMs are analyzed for liquid fraction and temperature distribution at nanofluid concentrations of 0.1%, 0.2%, and 0.3%. Key thermal parameters, including the Nusselt number, heat transfer coefficient, and pressure drop, are evaluated. Results reveal that using 0.3% nanofluids significantly improves heat transfer and accelerates melting and solidification. The rectangular fin configuration demonstrates superior performance, storing approximately 73,000 J compared to 55,000 J for the triangular fin. This improvement is attributed to optimized fin geometry, orientation, and enhanced thermal conductivity. Applications include solar heating, building energy management, and waste heat recovery. Furthermore, the Random Forest machine learning model effectively predicts energy storage performance, achieving an R^2 value of 0.99 for both training and testing datasets, confirming high predictive accuracy.

1. Introduction

Phase Change Materials (PCMs) are substances that store and release significant latent heat during their solid–liquid phase transitions. They are classified as organic, inorganic, or eutectic, and are applied across diverse sectors such as buildings, electronics, textiles, healthcare, automotive, aerospace, and solar energy. Organic PCMs offer chemical stability and consistent phase-change behavior, while inorganic PCMs provide higher thermal conductivity but often experience supercooling and phase separation.

In thermal energy storage systems, PCMs play a key role in balancing energy supply and demand. It analysed the temperature response of a PCM-based energy storage unit, focusing on cooler and heater positioning in two geometries: circular and rectangular. The results indicated that side heating significantly enhances the melting process, particularly in circular geometries, whereas top heating is less effective [1]. The melting of RT42 paraffin wax (PCM) in the presence of an air layer within a hemicylindrical enclosure is investigated. A 1 mm-thick air layer extended the complete melting time by 125%, while a 2 mm-thick air layer increased it by 225%. This demonstrates the considerable impact of ambient air on the efficiency of thermal storage units during charging [2]. Ahmed Belaadi et al. [3] explored thermal energy storage (TES) using PCMs under different scenarios. They analyzed contours of the liquid fraction, melting time (t-m), Nusselt number, and heat storage capacity (Q). The findings indicated that strategic changes in geometry significantly improve TES effectiveness and financial sustainability.

Arun Uniyal et al. [4] investigated the performance of a finned co-axial solar collector with evacuated tubes utilizing PCM for heat storage. Using solar radiation, it is demonstrated that the system effectively charges and discharges. The performance characteristics of packed beds utilizing encapsulated solid–solid phase change material (SS-PCM) for energy storage is also studied. The results emphasize its stability, flexibility, and absence of leakage, while also investigating the impact of storage tank height, SS-PCM capsule diameter, and heat transfer fluid velocity on the packed bed discharge process [5]. Jinquan Zheng et al. [6] introduced a mixed battery thermal management system (BTMS) for cylindrical battery packs. The liquid cold plate is designed with a wavy structure to improve temperature uniformity by utilizing coolant counterflow, maximizing PCM thickness, and controlling both the highest temperature and temperature differential.

Abubakar Mohammed et al. [7] investigated the combination of multi-phase change materials (m-PCMs) with a traditional parallel

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Nomenclature

Abbreviation

F_o	Fourier Number
LF	Liquid Fraction
MAE	Mean Absolute Error
ML	Machine learning
MSE	Mean Squared Error
Nu	Nusselt number
PCM	Phase Change Material
R^2	Coefficient of determinant
RF	Random Forests
RMSE	Root Mean Squared Error
TES	Thermal Energy Storage
SHAP	SHapley Additive exPlanations
LTES	Latent Thermal Energy Storage
SS- PCM	Solid-Solid phase change material
NF	Nanofluids
BTMS	Battery thermal management system
LHTES	Latent Heat Thermal Energy Storage
m- PCM	multi- phase change materials

Symbols

ρ	Density (kg/m^3)
cp	Specific Heat (J/kg K)
k	Thermal conductivity (W/mK)
$\vec{v}$	Velocity vector (m/s)
$\vec{g}$	Gravitational acceleration (m/s^2)
P	Pressure (Pa)
β	Thermal expansion coefficient (1/K)
T_m	Melting Temperature (K)
T	Temperature (K)
H	Total enthalpy (KJ/kg)
T_s	Solidus Temperature (K)
T_l	Liquidus Temperature (K)
μ	Viscosity (kg/ms)
L_h	Latent heat of fusion (kJ/kg)
HTC	Heat Transfer Coefficient (W/m^{2}K)
t	Time (seconds)
α	Thermal diffusivity (m^2/s)
L	Characteristic length (m)
Q	Heat flux (W/m^{2}K)

air-cooling battery system to enhance cooling performance at low power consumption rates. It found that proper PCM cell partitioning improves heat dissipation performance and reduces maximum temperature. A dual-layer PCM arrangement for lithium-ion batteries is also proposed to ensure stable operation under different ambient temperatures. It compared temperature variations of lithium-ion batteries with single-layer and dual-layer PCM configurations. This hybrid structure-controlled battery pack temperature uniformity and showed great potential for battery thermal management [8]. Another battery thermal management system (BTMS) is studied to improve cooling performance and temperature uniformity in electric vehicles (EVs). The system consisted of heat sinks with fluid channels and m-PCMs. The study revealed that increasing PCM thickness reduces temperature rise and improves temperature uniformity [9]. The unsteady phase change convection–conduction heat transfer of a lithium-ion battery is numerically investigated for solar vehicles. Results showed that heat conduction dominated the process, with the melting process producing a certain liquid phase fraction after 7 min [10]. Karem Elsayed Elfeky et al. [11] explored an optimized thermal management system for Li-ion batteries incorporating thin heat sinks, multiple PCMs, and air channels. Key findings indicated that a higher air inlet velocity initially reduced temperature rise, with greater benefits observed during extended discharge. It is also recommended that PCMs with higher melting temperatures be placed at the air outlet, while those with lower melting temperatures be positioned in the middle to more effectively lower battery temperature.

The melting process of phase change materials in a semi-cylindrical container is influenced by the presence of nanofluids. Results show that nanofluids accelerate the melting process and reduce melting time by 3%, 4%, and 5%, making them useful for large electronic device cooling [12]. Mohamed Boujelbene et al. [13] investigated the thermal performance of a semi-cylindrical Latent Heat Thermal Energy Storage (LHTES) unit during the melting process. They specifically examined how different copper fin configurations influence the unit's charging capability. Phase change materials like paraffin wax store and release heat effectively while maintaining a constant temperature during the solid–liquid transition. It is found that increasing the number of copper rods in a half-cylindrical cell reduced melting time by 45–52%, benefiting thermal energy storage applications [14]. Researchers also studied the effect of nanofluids on the PCM melting process, aiming to optimize heat transfer. Results show that increasing the nanofluid percentage improves performance, but also increases viscosity, which is a crucial factor for large electronic device cooling [15].

Shu-Bo Chen and S. Saleem [16] investigated Latent Thermal Energy Storage (LTES) systems using rectangular enclosures filled with PCM. Nine cases are considered, including pure PCM, nanostructured PCM, porous PCM, and nanostructured/porous PCM. Conclusions showed that the addition of nanoparticles by volume percentage improved melting performance. The impact of longitudinal fin position, Grashof number (Gr), and nanoparticle addition on heat transfer and melting rate of PCM is also investigated [17]. The effect of inclination angle and hybrid nano powders on convection-regulated melting in a rectangular TES unit is studied. It is found that a water–silica–MWCNT nanoparticle combination with a 0.01 vol fraction provided the shortest melting time and higher thermal storage capacity [18]. Ali Khaleel Kareem et al. [19] investigated heat transfer by turbulent flow in a cubic shell-and-tube heat exchanger using SiO_2–H_2O nanofluid. Through Computational Fluid Dynamics (CFD) modelling, they optimized the thermal performance. The findings revealed that decreasing the tube's Reynolds number of the hot inlet velocity significantly enhanced heat transfer rates. These insights are valuable for optimizing thermal systems and promoting energy conservation.

Machine learning, when integrated with PCM-based systems, is used for forecasting thermal behavior, identifying optimal materials, refining system design, and developing real-time control strategies. By training on experimental data or simulations, these models enable dynamic adjustments to operating parameters, thereby boosting efficiency and performance. It promotes the use of latent heat thermal energy storage techniques to conserve renewable energy [20]. The rise of machine learning has expanded thermal system datasets and improved thermal system optimization. In the electric vehicle industry, one of the main challenges is efficient cooling of lithium-ion batteries. Studies have shown that embedding nickel porous media around a $LiFeO_4$ cell decreases the maximum temperature and pressure drop [21]. Machine learning predictive models have also been applied to estimate the liquid fraction (LF) in photovoltaic (PV) systems integrated into buildings. Among four suggested configurations, the ARIMA (Autoregressive Integrated Moving Average) model outperformed others by reducing computational cost and improving thermal management, thereby supporting the development of sustainable and more effective energy solutions [22].

Beyond conventional rectangular and triangular fins, recent studies charging (melting) and discharging (solidification) processes are analysed. Key thermal and hydraulic parameters, including liquid fraction, temperature distribution, velocity magnitude, heat transfer coefficient (HTC), Nusselt number (Nu), pressure drop, energy storage, and energy release, were evaluated. The major findings of the study are summarized as follows:

5.1. Organic and inorganic PCMs

Among the organic PCMs, H395 exhibited the fastest melting rate and the highest final temperature, whereas H355 provided the highest latent heat capacity (230 kJ/kg) but showed a slower melting process. Among the inorganic PCMs, PCM-C demonstrated the fastest melting and highest temperature due to its relatively high thermal conductivity, while PCM-S exhibited a significantly slower melting rate because of its lower thermal conductivity. PCM-C is suitable for applications requiring rapid thermal response, whereas PCM-M, with a latent heat capacity of 310 kJ/kg, is more appropriate for applications demanding higher energy storage density.

5.2. Effect of nanofluid concentration

The 0.3% nanoparticle volume fraction significantly enhanced both charging and discharging performance compared with the 0.1% and 0.2% cases. The complete melting time is reduced by 7.76% for the rectangular fin configuration and by 2.11% for the triangular fin configuration when using 0.3% nano multi-PCM compared with 0.1%. Similarly, the complete solidification time is reduced by 4.48% and 10.14% for the rectangular and triangular fin configurations, respectively. However, the 0.3% nanoparticle concentration also increased viscosity, resulting in a higher pressure drop and indicating a thermal–hydraulic trade-off between enhanced heat transfer and flow resistance.

5.3. Comparison of fin geometries

Rectangular fins (Case a) consistently outperformed triangular fins (Case b) during the charging process, achieving a liquid fraction of 1.0 at 3500 s, compared with 0.9742 for Case b. During discharging, Case a also demonstrated faster solidification, with remaining liquid fractions of 0.0668 and 0.1155 for Cases a and b, respectively, at 3500 s.

5.4. Heat transfer and pressure drop characteristics

Case a achieved a higher peak HTC (approximately 17.5 $W/m^2 \cdot K$) compared with Case b (approximately 14 $W/m^2 \cdot K$) and maintained a higher Nusselt number throughout the charging process. Case a also exhibited a smaller negative pressure drop during both charging and discharging processes, indicating lower flow resistance and improved fluid circulation. Nevertheless, increasing the nanoparticle concentration to 0.3% increased the absolute pressure drop, emphasizing the need to balance heat transfer enhancement with hydraulic performance.

5.5. Machine learning prediction

The Random Forest regression model accurately predicted the thermal energy storage performance, achieving an R^2 value of 0.999 for both training and testing datasets. SHAP analysis indicated that time, liquid fraction, and fin geometry were the most influential parameters affecting energy storage performance.

The findings of this study highlight the potential of the proposed thermal energy storage system for real-world applications. Among the investigated configurations, the rectangular fin arrangement with a 0.3% nanofluid concentration showed the best performance by storing nearly 73,000 J of energy, whereas the triangular fin configuration stored about 55,000 J. In addition, the melting time is reduced by 7.76%, indicating faster heat charging capability. These characteristics make the system well suited for solar thermal energy storage applications, where rapid heat absorption during the daytime and stable heat release during nighttime are important. Moreover, the improved heat transfer performance obtained with nanofluid-enhanced PCMs makes the proposed design attractive for industrial waste heat recovery, where unused thermal energy from exhaust gases or process streams can be recovered and reused efficiently.

The developed Random Forest and SHAP model achieved an R^2 value of 0.99, demonstrating its ability to accurately predict thermal energy storage performance. This approach can help engineers evaluate and optimize system designs more quickly without performing time-consuming CFD simulations for every case. Overall, the results of this work provide useful insights for designing advanced latent heat thermal energy storage (LHTES) systems for renewable energy utilization, building thermal management, and industrial energy recovery applications.

5.6. Broader Implications and Future Scope

The findings of this study have important practical uses for designing high-performance thermal storage systems in buildings and factories. By combining multi-layer phase change materials (PCMs) with rectangular fins, the system can absorb and release heat naturally using fluid buoyancy, applications that helps save energy in building climate control and industrial waste heat recovery without needing costly electric pumps. Additionally, using machine learning combined with SHAP analysis shows that thermal energy systems can be evaluated and optimized very quickly, significantly reducing the need for long, expensive computer simulations and making the design process much faster for engineers. While this study shows great results, several areas are open for future research to improve the system. Future work should test different fin shapes using the exact same weight or volume to isolate whether performance improvement comes purely from fin design or from having more material. Researchers should also use smart multi-objective algorithms to find the perfect setup, including the ideal number of PCM layers, their exact order, and how thick each layer should be. Additionally, future simulations should employ advanced two-phase modeling to study how nanoparticles behave over time, closely examining particle grouping and settling across many heating and cooling cycles.

CRediT authorship contribution statement

Iskander Tlili: Writing – review & editing, Supervision, Formal analysis, Validation. **S. Anitha:** Writing – review & editing, Supervision, Data curation, Formal analysis. **Madhu Aneja:** Writing – review & editing, Conceptualization, Data curation, Investigation. **M. Ramanipriya:** Writing – original draft, Validation, Data curation, Formal analysis, Investigation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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