Dynamically enhanced phase change materials for rapid thermal energy storage

Xinyu Huang[1,*]
[1]Department of Mechanical Engineering, National University of Singapore, Engineering Drive 117575, Singapore
*Correspondence: xyhuang@nus.edu.sg
Received: May 14, 2026; Accepted: July 13, 2026; Published Online: July 16, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100183

Citation: Huang X. (2026). Dynamically enhanced phase change materials for rapid thermal energy storage. *The Innovation Energy* **3**:100183.

BACKGROUND

The growing deployment of renewable energy, industrial waste heat recovery, and electric vehicles has created a strong demand for thermal batteries that combine high energy density with rapid charging. Phase change material (PCM)-based thermal batteries are promising because they store heat as latent heat over a narrow temperature range. However, it remains difficult to achieve high storage density and fast charging at the same time. PCMs with high melting enthalpy usually have low thermal conductivity, whereas conventional composite PCMs rely on conductive fillers that occupy latent-heat storage volume and reduce energy density.

Recent research has shown that the charging bottleneck of PCMs is not only determined by their inherent thermal conductivity but also by the interface heat transfer during the phase change process. In traditional phase change thermal batteries, the phase interface gradually moves away from the heating boundary, and the increasing liquid layer increases the thermal resistance. Li et al.[1] provided a representative solution by designing a composite coating that can achieve slip-enhanced close contact melting within the sealed thermal battery. The slip interface reduces friction between the solid PCM and the heated wall, allowing the remaining solid PCM to continuously slide or sink toward the heat source under gravity or external loading. The newly melted liquid is squeezed away from the contact region, so the heat-transfer path remains a thin liquid layer rather than a progressively thickening insulating layer. Using organic phase change materials, this prototype device achieved a power density of 1100 ± 2% kilowatts per cubic meter, without sacrificing energy density.

Dynamically enhanced PCMs are organized into four active-regulation families. Quadrant 01 shows vibrational and acoustic stimuli, in which mechanical vibration, ultrasonic excitation, acoustic streaming, and microbubble perturbations disturb the thermal boundary layer and accelerate melt-front migration. Quadrant 02 presents field-modulated enhancement, where electric or magnetic fields regulate ion-drag flow, liquid-phase motion, particle alignment, or conductive-network reconstruction. Quadrant 03 illustrates dynamic and mechanical forcing, including rotation and impeller-driven mixing, which redistribute solid and liquid phases and reduce stagnant thermal zones. Quadrant 04 shows intelligent flow and pulsation, where high-momentum pulsed jets directly impinge on the melting front and suppress the growth of the liquid thermal boundary layer. The central cutaway highlights the solid, mushy, and liquid regions of a PCM storage unit and the interfacial resistance that limits charging power. The multi-scale synergy concept links microscopic interactions, meso-scale flow and structural evolution, and system-scale performance, showing how external driving inputs can be translated into interface regulation, latent-heat utilization, and high-rate thermal storage for solar thermal integration, industrial waste heat recovery, and electric mobility.

This commentary focuses on dynamically enhanced phase change materials for rapid thermal energy storage. Despite these advances, a unified framework is still needed to connect external driving inputs with interface evolution, flow-field reconstruction, and latent-heat utilization, which this commentary aims to outline.

RECENT PROGRESS AND EXISTING CHALLENGES

For rapid thermal energy storage, the major limitation of conventional PCMs is the progressive increase of thermal resistance during melting and solidification. In a typical charging process, the molten layer continuously thickens between the heat source and the solid PCM, forcing the phase change interface to move away from the heating surface. As a result, the heat transfer rate decays with time, and the high latent heat of PCMs cannot be fully converted into high power density. Traditional enhancement strategies, including fins, metal foams, porous skeletons, and thermally conductive fillers, can shorten the heat conduction path and improve the initial thermal response. However, these passive methods generally introduce extra mass, occupy latent-heat storage volume, and provide fixed thermal properties that are difficult to adapt to fluctuating thermal loads. More importantly, they do not solve the central unresolved problem: the inability to actively regulate melt-front migration, liquid-layer growth, and time-dependent interfacial resistance during repeated charging and discharging.

A representative progress is the dynamic PCM strategy based on pressure-enhanced close contact melting. Fu et al.[2] proposed applying pressure to keep the solid PCM close to the heat source while continuously removing the molten phase from the interface. In this configuration, the melt-front distance is confined to a thin and nearly constant liquid layer, which prevents the accumulation of time-dependent interfacial thermal resistance. Compared with conventional bulk PCMs, this approach enables stable surface temperature control and simultaneously improves effective energy density and power density. Using paraffin wax and gallium, the system achieved effective energy and power densities of 230 J cm^{-3} and 0.8 W cm^{-3}, and 480 J cm^{-3} and 1.6 W cm^{-3}, respectively.

Magnetic field modulation provides another approach for dynamic phase change materials. Recent studies have shown that the magnetic field can control the aggregation and arrangement of magnetic nanoparticles in composite phase change materials, thereby reconstructing the internal heat transfer path. By adjusting the direction of the nanoparticle aggregates relative to the main heat flow, the same phase change material system can achieve enhanced heat diffusion under high heat flow conditions and insulation in standby mode. This switchable behavior is mainly effective in the liquid or partially molten state; once the PCM solidifies, the particle arrangement is locked until the next melting cycle. The magnetic composite phase change material based on Fe_3O_4@CNT nanoparticles effectively reduced the effective thermal resistance by 1.8 times and decreased the temperature fluctuation of electronic components by 10.8°C under dynamic intermittent loading conditions.[3] However, magnetic field modulation is highly dependent on the magnetic field strength, particle mobility, aggregation stability, and the liquid content of the phase change material. Once the phase change material solidifies, the rearrangement of nanoparticles is restricted, so it is necessary to synchronize the magnetic field drive with the phase change cycle.

Vibrational and acoustic stimuli are also active methods for enhancing phase-change heat transfer. Mechanical vibration can disturb molten PCMs, strengthen relative liquid motion, and enhance convective transport without directly reducing the energy storage density. Acoustic stimulation further introduces acoustic streaming and microbubble-induced perturbations near the heat transfer surface, which can thin the liquid thermal boundary layer and accelerate melt-front migration.[4] Rotation can further regulate the relative distribution of solid PCMs, liquid PCMs, and heat transfer surfaces. In a triplex-tube latent heat thermal energy storage system, rotation at 1 rpm reduced the solidification time by 83.85% and increased the heat release rate by 4.98 times compared with the static case. However, these mechanical methods introduce additional moving parts, control complexity, operating energy consumption and sensitivity to vibration frequency, amplitude, rotation speed and system geometry.[5]

Overall, recent progress indicates that PCM enhancement is shifting from static thermal-conductivity improvement to dynamic regulation of phase-change heat transfer. Strategies such as pressure-enhanced close-contact

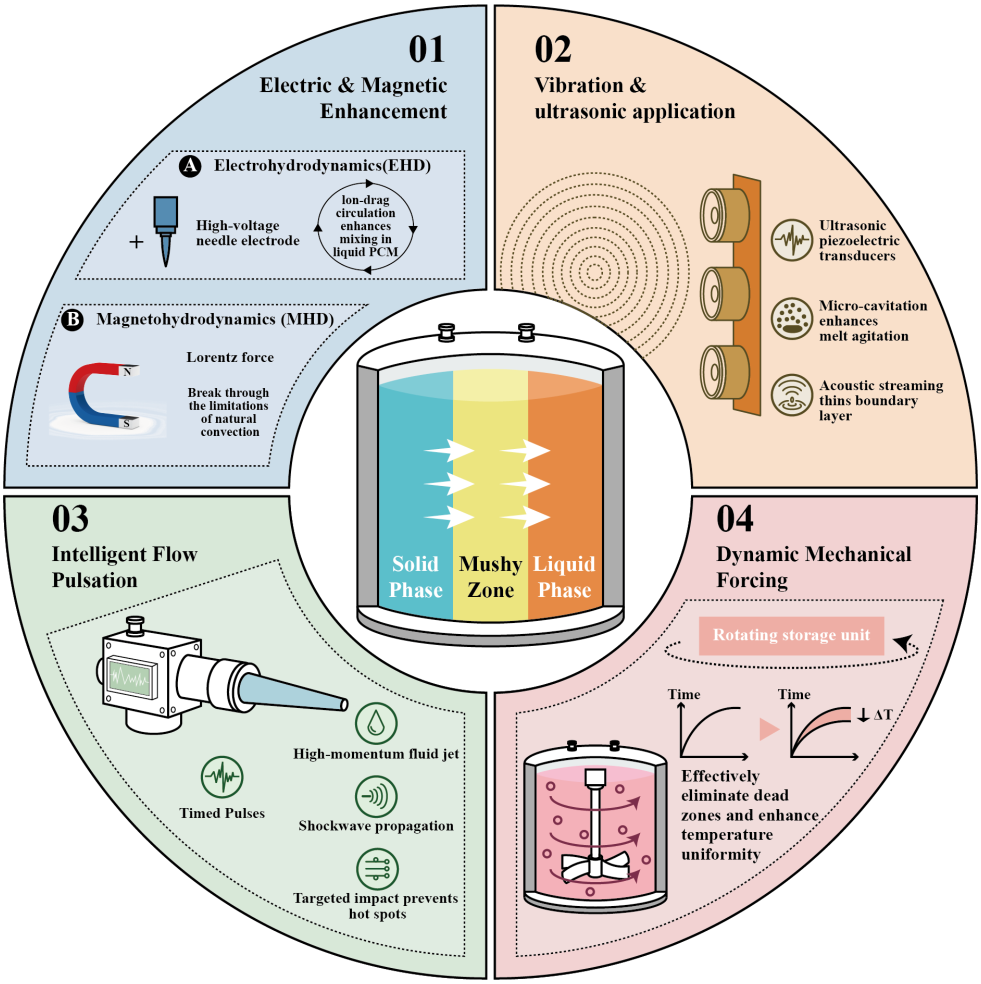

Figure 1. Four dynamic PCM enhancement families and their multi-scale synergy from interface regulation to system-level thermal storage applications.

melting, magnetic-field regulation, vibrational and acoustic stimuli, and rotational forcing aim to control melt-front evolution, interfacial thermal resistance, and liquid-phase flow in real time. The remaining challenges lie in balancing power density and energy density, reducing external driving costs, ensuring cycling reliability, and developing compact structures for practical thermal storage and thermal management systems. Future research should establish a unified framework that links external driving inputs, interface evolution, flow-field reconstruction, and heat storage/release dynamics, thereby enabling dynamically enhanced PCMs with rapid thermal response and high latent-heat utilization.

CURRENT CHALLENGES AND FUTURE SOLUTIONS

To break through the technical bottlenecks of high-density thermal storage and rapid heat release, dynamic enhanced phase change materials have become a promising development direction for the next-generation phase change thermal batteries. However, to achieve rapid, stable and intelligent thermal energy storage, overcoming the following key challenges is crucial.

(1) The dynamic phase change heat transfer mechanisms under vibrational and acoustic stimuli, field-modulated enhancement, dynamic and mechanical forcing, and intelligent flow and pulsation need to be clarified. These active strategies can regulate the melting front, reduce the thermal resistance of the liquid layer, and enhance the liquid relative flow. At the same time, deep learning based on physical principles can be used to predict the non-uniform evolution of complex phase change interfaces. This helps to reveal the relationship between external energy input, interface migration, flow field reconstruction and latent heat utilization.

(2) For dynamic enhanced phase change material systems, precise sensing and real-time control are essential. Temperature sensors, heat flow sensors, pressure monitoring units and flow diagnostic devices can provide evidence for determining the thermal state of the phase change material. On this basis, machine learning and model predictive control can adjust the intensity of pulse heating, pressure loading, acoustic wave frequency, magnetic or electric field direction, rotation speed and flow pulsation. This will enable phase change material thermal batteries to switch between rapid charging and controlled heat release.

(3) Dynamic enhancement usually increases power density, but also introduces additional equipment, increases energy consumption and reliability risks. AI-driven multi-objective optimization can balance energy density, power density, driving cost, system compactness and cycle stability. Digital twins can further simulate long-term charging and discharging processes before prototype manufacturing. Together, these advances will support the development of scalable and durable phase change material thermal batteries for solar thermal utilization, industrial waste heat recovery, and electric vehicles.

REFERENCES

1. Li Z.R., Hu N., Wang Z.B., et al. (2026). Pulse heating and slip enhance charging of phase-change thermal batteries. *Nature* **649**:360–365. DOI:10.1038/s41586-025-08462-9
2. Fu W., Yan X., Gurumukhi Y., et al. (2022). High power and energy density dynamic phase change materials using pressure-enhanced close contact melting. *Nat. Energy* **7**:270–280. DOI:10.1038/s41560-022-01063-6
3. He J., Yang L., Wang Q., et al. (2026). Dynamic thermal management under variable operating conditions through magnetic field control. *Nat. Commun.* **17**:1958. DOI:10.1038/s41467-026-67341-7
4. Lan M., Wu J., Wang X., et al. (2026). Study on phase change heat storage assisted with acoustic flow effect under different acoustic vibration area. *J. Energy Storage* **156**:121570. DOI:10.1016/j.est.2026.121570
5. Huang X., Li F., Guo J., Li Y., et all. (2024). Design optimization on solidification performance of a rotating latent heat thermal energy storage system subject to fluctuating heat source. *Appl. Energy* **362**:122997. DOI:10.1016/j.apenergy.2024.122997

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The author declares no competing interests.