Numerical Investigation of Nanofluid-Enhanced Phase Change Materials for Advanced Thermal Energy Storage

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Abstract

Global emphasis on sustainable energy solutions has increased the demand for high performance thermal energy storage (TES) systems. Phase-change materials (PCMs) are central to this research because of their high energy-storage density at nearly constant temperatures. However, their widespread implementation is impeded by their inherently low thermal conductivity, which results in low charging and discharging rates. Although the dispersion of nanoparticles has been investigated to address this issue, the synergistic potential of advanced nanofluids in dynamic phase-change environments remains a critical and unexplored area.

This study presents a comprehensive numerical investigation to evaluate the thermal enhancement of a PCM integrated with novel nanoparticles. The model integrates phase change with non-Newtonian fluid dynamics to capture transient melting and solidification processes, including the critical effects of natural convection. The results demonstrate that PCM-Nanofluid materials significantly accelerate the phase change process, leading to a substantial reduction in the total melting time and an increase in the heat transfer rate compared to pure PCM. Furthermore, this study aims to identify an optimal nanoparticle volume fraction that maximizes the thermal performance by leveraging the synergistic effects between enhanced conduction and modified convection dynamics. The findings will provide fundamental insights and practical design guidelines for developing next generation, high-efficiency latent heat thermal energy storage systems and contribute significantly to the advancement of renewable energy technologies.