



Full Length Article

Numerical investigation of MHD phase change heat transfer of Al_2O_3 -CuO-MWCNT ternary hybrid nanofluids using a Crank-Nicolson scheme

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ARTICLE INFO

Keywords:

Phase change material (PCM)
Ternary hybrid nanofluid
Magnetohydrodynamics (MHD)
Crank-Nicolson method
Enthalpy-porosity technique

ABSTRACT

Latent Heat Thermal Energy Storage (LHTES) systems are critical for renewable energy integration, yet their performance is often limited by the low thermal conductivity of conventional Phase Change Materials (PCMs). This study numerically investigates the accelerated melting of a novel Al_2O_3 -CuO-MWCNT ternary hybrid nanofluid in a rectangular enclosure under the influence of a uniform magnetic field. A robust, unconditionally stable Crank-Nicolson Alternating Direction Implicit (ADI) scheme is developed to solve the transient Navier-Stokes and energy equations coupled with the enthalpy-porosity method. The numerical code is rigorously validated against the analytical solution of the Stefan problem and grid independence tests. The results demonstrate that the inclusion of ternary hybrid nanoparticles, particularly Multi-Walled Carbon Nanotubes (MWCNTs) modeled with the Hamilton-Crosser shape factor, significantly enhances the thermal conductivity and melting rate compared to pure paraffin. Furthermore, the application of a magnetic field is shown to suppress natural convection currents, shifting the heat transfer mechanism from convection-dominated to conduction-dominated, thus providing a mechanism to control the melting front progression. This study provides new insights into optimizing LHTES systems by combining advanced nanotechnology with magnetohydrodynamic flow control.

1. Introduction

The escalating global demand for energy, driven by rapid industrialization and population growth, has precipitated a critical need for sustainable and efficient energy systems. In this landscape, Thermal Energy Storage (TES) has emerged as a pivotal technology for correcting the temporal mismatch between energy supply and demand, particularly for intermittent renewable sources like solar and wind [1]. Among the various TES methods, Latent Heat Thermal Energy Storage (LHTES) utilizing Phase Change Materials (PCMs) is widely regarded as the most promising due to its high energy storage density and ability to store heat at nearly constant temperatures [2]. However, the commercial viability of conventional organic PCMs, such as paraffin waxes and fatty acids, is severely restricted by their inherently low thermal conductivity (typically $0.2 \text{ W/m}\cdot\text{K}$), which leads to sluggish charging (melting) and discharging (solidification) rates [3]. Overcoming these thermal limitations is critical for deploying LHTES in high-stakes practical applications, such as the transient thermal management of high-power density electronics, energy buffering in Concentrated Solar Power (CSP) plants, and advanced aerospace cooling systems where external magnetic fields can provide active flow control.

To circumvent these thermal limitations, advanced heat transfer enhancement techniques have been extensively explored. The dispersion of high-conductivity nanoparticles into PCMs to form “nano-enhanced PCMs” (NePCMs) has proven to be a highly effective strategy [4,5]. While early research focused on mono-nanofluids, the scientific frontier has recently shifted toward ternary hybrid nanofluids, which combine three distinct types of nanoparticles to achieve synergistic enhancements in thermophysical properties that surpass those of mono and binary hybrid systems [4]. Recent experimental work by Venkatakrishnan and Palanisamy (2024) highlighted the superior performance of combining Aluminum Oxide (Al_2O_3), Copper Oxide (CuO), and Multi-Walled Carbon Nanotubes (MWCNTs) in phase change applications [6]. This specific ternary combination leverages the chemical stability of Al_2O_3 , the high thermal capacity of CuO, and the exceptional ballistic thermal conductivity of MWCNTs. Furthermore, recent numerical studies by Jamaludin (2024) and Adnan (2025) emphasize the critical role of nanoparticle geometry, advocating for the use of the Hamilton-Crosser model with shape factors (n) to accurately predict the thermal percolation networks formed by cylindrical MWCNTs [7,8].

In parallel with material advancements, active flow control via Magnetohydrodynamics (MHD) offers a non-intrusive mechanism to regu-

E-mail address: shivara0374@gmail.com<https://doi.org/10.1016/j.thradv.2026.100192>

Received 11 June 2026; Received in revised form 10 July 2026; Accepted 20 July 2026

Available online 22 July 2026

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