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Melting Process of Carreau Non-Newtonian Nano-phase change material inside Cylindrical Energy Storage System rotating

Alireza kazemi[1],Mohsen izadi[2*],ehsanolah assareh[1], Ali Ershadi[1]

[1]Department of Mechanical Engineering, Dezful Branch, Islamic Azad University, Dezful, Iran

[2]Mechanical Engineering Department, Faculty of Engineering, Lorestan University, Khorramabad, Iran

Extended Abstract

Introduction

Phase change materials (PCMs) have attracted considerable attention in thermal energy storage systems because of their ability to store and release large amounts of thermal energy during phase transition. Their applications extend to renewable-energy systems, particularly solar thermal technologies, thermal management of electronic devices, and heat storage units. However, the relatively low thermal conductivity of many PCMs can significantly restrict the rate of heat transfer and consequently increase the time required for charging and discharging thermal energy storage systems. The development of geometrical and material-based techniques, including porous structures, thermal fins, and nanoparticles, has therefore become an important research direction for improving PCM thermal performance.
The thermal behavior of PCMs becomes more complex when the molten phase exhibits non-Newtonian characteristics. In such systems, the apparent viscosity varies with the local shear rate, thereby influencing fluid motion and the relative contributions of conduction and natural convection during melting. In addition, the presence of a porous matrix can substantially suppress fluid motion and alter the balance between conductive and convective heat transfer. Previous investigations have demonstrated that thermal fins can considerably accelerate PCM melting, whereas porous media and nanoparticles can modify the effective thermal transport mechanisms. However, the combined effects of non-Newtonian behavior, porous structures, thermal fins, and chamber orientation have received comparatively limited attention. Accordingly, the present study numerically investigates the melting behavior of a non-Newtonian nano-enhanced PCM contained within a porous cylindrical enclosure equipped with copper thermal fins. Particular attention is given to the influence of the chamber inclination angle on the flow field, temperature distribution, melting front, average Nusselt number, velocity field, and liquid fraction. The study aims to clarify whether changing the orientation of such a porous thermal storage configuration can effectively modify its heat-transfer and melting characteristics. The investigated configuration consists of a cylindrical porous matrix saturated with a kerosene–alumina PCM, providing a representative model for advanced latent heat thermal energy storage systems.

2. Materials and Methods

A two-dimensional axisymmetric numerical model was developed to simulate the melting process of a non-Newtonian nano-enhanced PCM in a porous cylindrical enclosure equipped with copper thermal fins. The porous matrix was considered to be made of iron, with its void spaces saturated by a kerosene–alumina PCM. A heated working fluid

flows upward through the central tube and supplies thermal energy to the storage domain, while the upper and lower surfaces and the external cylindrical wall are thermally insulated. Three copper thermal fins are incorporated into the configuration to enhance heat transfer from the heated region toward the PCM. The enthalpy–porosity formulation was employed to describe the phase transition and the evolution of the solid–liquid interface. The molten nano-enhanced PCM was modeled as a non-Newtonian fluid using the Carreau model, allowing the variation of apparent viscosity with shear rate to be incorporated into the governing equations. The thermophysical properties of the kerosene–alumina mixture were assumed to remain constant within each phase, while the alumina nanoparticles were considered to remain uniformly distributed throughout the PCM during the melting process. Natural convection in the molten region was modeled under the Boussinesq approximation. The governing continuity, momentum, and energy equations, together with the corresponding initial and boundary conditions, were formulated in cylindrical coordinates and subsequently transformed into dimensionless form. The coupled equations were solved using the finite-element method. The computational domain was discretized using triangular elements, with local mesh refinement applied around the thermal fins and the walls to improve the resolution of temperature and velocity gradients. Grid independence was examined using five different mesh sizes at three representative Fourier numbers. The average Nusselt number, average velocity, and liquid fraction were selected as the principal criteria for assessing numerical independence. The fourth mesh, consisting of approximately **540,098 domain elements and 2,200 boundary elements**, was selected as the appropriate computational grid because it provided sufficiently small variations in the monitored outputs while maintaining reasonable computational cost. The numerical formulation was further assessed through comparison with previously published numerical and experimental results. The close agreement between the predicted and reference melting patterns provided evidence of the reliability of the developed computational model and its capability to reproduce the principal characteristics of PCM melting under natural-convection conditions.

3. Results and Discussion

The numerical results demonstrate that the melting process is governed by the interaction between heat conduction through the porous structure and natural convection within the molten PCM. Because the entire storage region is occupied by a porous matrix, fluid motion is considerably restricted. Consequently, conductive heat transfer remains the dominant mechanism and the influence of buoyancy-driven convection is relatively limited. A major finding of the study is that changing the inclination angle of the chamber with respect to the horizontal direction produces **no significant modification in the thermal and melting characteristics**. The temperature contours and melting-front patterns remain substantially similar for the investigated inclination angles. Likewise, the average Nusselt number and liquid fraction exhibit no appreciable variation with chamber orientation. This behavior can be attributed primarily to the presence of the porous matrix, which suppresses the buoyancy-induced motion of the molten PCM. As a result, changes in the direction of the gravitational force relative to the enclosure have only a minor influence on the overall heat-transfer process. The results further indicate that the non-Newtonian characteristics of the molten PCM must be considered when evaluating the heat-transfer behavior of the storage system. The use of the Carreau model enables the shear-dependent viscosity of the molten phase to be incorporated into the momentum equation and provides a more realistic representation of the flow behavior compared with a conventional Newtonian approximation. Nevertheless, the strong resistance imposed by the porous matrix limits the development of vigorous convective circulation. The role of thermal enhancement strategies can also be interpreted in relation to previous studies. Earlier numerical and experimental investigations have shown that increasing the number of thermal fins can decrease the melting time and increase the overall heat-transfer rate. Similarly, the combined use of porous structures and nanoparticles can modify the effective thermal conductivity and liquid fraction of PCM systems. However, the present results suggest that once the storage domain is strongly dominated by conduction because of its porous structure, changes in buoyancy resulting from enclosure inclination are insufficient to produce a meaningful alteration in the melting rate. An important implication of these findings is that the orientation of the storage unit may not constitute a critical design parameter for this class of porous PCM systems. This is particularly relevant for practical thermal energy storage units where installation constraints may require different orientations. If the porous matrix remains sufficiently effective in suppressing large-scale natural convection, comparable thermal performance can be expected over a range of inclination angles.

4. Practical Implementation and Validation

The developed numerical framework provides a useful computational tool for the design and optimization of latent heat thermal energy storage systems employing non-Newtonian PCMs, porous matrices, nanoparticles, and thermal fins. The model can be applied to evaluate the influence of geometric configuration and operating conditions without requiring extensive experimental testing for every design case. The validation procedure is an important strength of the study. The numerical predictions were compared with available experimental observations of PCM melting in an enclosure equipped with thermal fins. The predicted evolution of the melting front showed a close correspondence with the experimentally observed progression over different melting times, particularly in the upper regions of the enclosure where the melting front advances more rapidly. This agreement confirms the capability of the developed computational model to capture the principal heat-transfer mechanisms governing PCM melting. From an engineering perspective, the results indicate that the use of porous structures can provide a degree of orientation independence in thermal storage systems. Therefore, designers may have greater flexibility in positioning cylindrical PCM storage units without substantially compromising their melting performance. At the same time, thermal fins remain an important design feature for enhancing heat transfer, particularly when the objective is to compensate for the intrinsically low thermal conductivity of PCM materials.

5. Conclusions

The numerical investigation of melting of a non-Newtonian nano-enhanced PCM in a porous cylindrical chamber equipped with thermal fins led to the following main conclusions:

- The enthalpy–porosity method combined with the Carreau non-Newtonian model provides an appropriate framework for simulating the melting behavior of the investigated PCM system.
- The finite-element computational model showed satisfactory mesh independence, with the selected mesh containing approximately 540,098 domain elements and 2,200 boundary elements.
- The presence of the porous matrix significantly restricts buoyancy-driven fluid motion and causes heat conduction to become the dominant heat-transfer mechanism.
- Changing the chamber inclination angle has no significant effect on the temperature contours, melting-front evolution, average Nusselt number, or liquid fraction.
- The limited sensitivity to orientation is mainly attributed to suppression of natural convection by the porous matrix; consequently, changes in buoyancy forces do not substantially modify the melting process.
- Thermal fins remain an effective means of improving heat transfer and accelerating PCM melting, whereas chamber orientation is a relatively weak design parameter for the investigated porous configuration.
- The developed numerical model can be used as a practical design and optimization tool for latent heat thermal energy storage systems involving non-Newtonian PCMs and porous heat-transfer structures.

Overall, the findings demonstrate that the thermal behavior of a porous PCM storage system is controlled primarily by the competition between conduction through the porous matrix and natural convection in the molten phase. When the porous structure sufficiently suppresses fluid motion, the orientation of the storage chamber becomes a secondary parameter. This observation can contribute to the development of more flexible and compact thermal energy storage systems for renewable-energy and thermal-management applications.

Key words: Melting process, Natural convection, Conjugate heat transfer, porous media, Carreau non- Newtonian fluid, nanofluid.

*corresponding author: izadi.m@lu.ac.ir

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