



Experimental and numerical investigation of melting of phase change material/nanoparticle suspensions in a square container subjected to a constant heat flux



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ABSTRACT

Melting of *n*-octadecane with CuO nanoparticle suspensions in a square enclosure is studied experimentally and numerically. The container is subjected to a constant heat flux on one side, while the other sides are thermally insulated. The experimental study entailed recording the time-dependent temperatures at different locations inside the cell. The finite element method (FEM) is used to solve the coupled continuity, momentum, and energy coupled equations numerically. The model is validated and the results exhibited a good agreement with previous related work. The agreement between the current experimental and simulated results is reasonable. The impacts of the nanoparticle loading, the Rayleigh number, and the subcooling are analyzed. The experimental and numerical results indicate that the nanoparticle loading has a positive effect on raising the thermal conductivity of the PCM/nanoparticle composite, increasing the temperature of the composite and augmenting heat transfer rate which results in decreasing the charging time. Development of the melting interface and melt fraction volume are improved with the increasing of the nanoparticle concentration. Caution should be taken for higher values of nanoparticle concentration due to effects of increasing viscosity and possibility of agglomeration and precipitation. The effect of natural convection is pronounced in the upper part of the cell, while the lower region is characterized by conduction-dominated heat transfer. This effect intensifies with the increase of the supplied heat flux (i.e. raising the value of the Rayleigh number) which causes expediting of the melting process. The shape of the melting interface is affected highly by the competing heat transfer mechanisms. Parallel-to-wall flat shape interface is present in the conduction-dominant regime, while curved shape of the interface emphasizes development of natural convection. The impact of subcooling has a negative influence on the melting process in which the high value of subcooling will prolong the charging time.

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1. Introduction

Phase change materials (PCM) are considered to be promising thermal storage materials for adjusting the time delays associated with energy supply and demand. Thermal energy can be stored via latent, sensible, and chemical options. Latent heat thermal energy storage has advantages of high energy density with small storage volume and, in principle, allows for energy storage at a nearly constant (phase change) temperature during melting and solidification. The main criterion to select a PCM for a particular application is its phase change temperature. However, other important parameters must also be taken into account for an

appropriate decision. These parameters include high values of the latent heat and thermal conductivity, in addition to stability to cycling [1,2]. Farid et al. [3] reviewed PCM materials, their encapsulation and their diverse applications. The problems associated with the application of PCM with regard to the materials and methods used to contain them were also discussed. In light of its advantages and versatility, PCM-based thermal storage technologies are well-suited to serve important practical interests such as thermal storage of solar energy, thermal management of electronic devices, thermal storage in buildings, cooling of engines, etc.

Melting of phase change materials in rectangular containers has attracted significant interest due to its wide-ranging engineering applications in such fields as casting, metallurgy and thermal energy storage. The phenomena associated with melting initiated from isothermal heating from one or more sides of containers are covered by a great number of analytical, numerical, and experimental studies [4–18]. These studies clearly point to the eventual

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Nomenclature

C_p	specific heat at constant pressure	μ	dynamic viscosity
g	gravitational acceleration	ν	kinematic viscosity
H	height of the enclosure	ρ	density
k	thermal conductivity	λ	latent heat of fusion
p	pressure	ϕ	volume fraction
q_w	constant wall heat flux	ϕ_{wt}	weight fraction
Ra	Rayleigh number, $\frac{g\beta q_w H^4}{k_i \alpha_i \nu_i}$	Subscripts	
Sb	subcooling, $T_m - T_{ini}$	<i>ini</i>	initial
Ste	Stefan number, $\frac{C_{pl} q_w H}{k_i \lambda}$	<i>l</i>	liquid PCM
t	time	<i>m</i>	melting
T	temperature	<i>n</i>	nanoparticle-enhanced PCM
ΔT_m	melting temperature range, $T_{liquidus} - T_{solidus}$	<i>p</i>	nanoparticle solid
u, v	velocity components	<i>pcm</i>	phase change materials
x, y	Cartesian coordinates	<i>ref</i>	reference
Greek symbols		<i>s</i>	solid PCM
α	thermal diffusivity		
β	thermal expansion coefficient		

significant role of buoyancy-driven convection, while diffusion-dominated thermal transport was important at early stages of melting. Among these studies, a few articles were dedicated to constant heat flux-sustained melting. Zhang et al. [19] presented experimental results on the melting process of *n*-octadecane in a rectangular enclosure subjected to a constant heat flux. The results showed that natural convection has a significant effect on the shape of the solid–liquid interface and the influence becomes more pronounced with increasing the Rayleigh and Stefan numbers. Ho and Chu [20] simulated numerically using the finite difference method (FDM) the transient heat penetration through a vertical rectangular composite cell filled with a solid–liquid PCM and an air layer. Jianhua et al. [21] studied experimentally the melting process of *n*-octadecane in a rectangular cavity with three discrete protruding heat sources on its bottom surface. The surface temperatures of the heat sources were measured by thermocouples (TC) and the solid–liquid interface motion was recorded photographically. Fusion mechanism of a pure substance (gallium) was examined numerically by Mbaye and Bilgen [22]. The rectangular enclosure was subjected to a constant heat flux on its left vertical wall, constant temperature on its right wall, whereas adiabatic condition was maintained on its two horizontal walls. It was found that an important parameter controlling heat transfer and melting velocity was the applied heat flux. Pal and Joshi [23] studied computationally and experimentally the melting of an organic phase change material (*n*-triacontane) in a tall enclosure with an aspect-ratio of 10 by supplying a constant heat flux on one side. They reported that natural convection plays a dominant role during the initial stages of melting, and at a later time, the strength of natural convection diminishes as melting is completed. An analytic study was presented by Hamdan and Al-Hinti [24] for melting process of a solid phase change material contained in a rectangular enclosure heated from a vertical side maintained at a constant heat flux. The propagation and the inclination of the solid–liquid interface along with the time-evolution of the melted fraction were studied and evaluated. Faraji and El Qarnia [25] studied numerically the melting of *n*-eicosane in a rectangular enclosure heated with three protruding heat sources with a constant and uniform volumetric heat generation on one side. El Qarnia et al. [26] investigated numerically the same model to examine the impact of several key parameters of the PCM-based heat sink on its cooling capacity. Samara et al. [27] presented and compared two methods enabling

the simulation of PCM melting while accounting for both conduction and natural convection.

Regarding the low thermal conductivity shortcoming of PCM, specially during melting, which could result in lower heat transfer rates during melting/freezing processes, several ideas and systems have been proposed as thermal conductivity enhancers (TCE) in the literature. The enhancing techniques can be categorized into two groups. The first type of TCE involve introducing fixed structures such as fins [28–32], fiber brushes [33,34], and porous materials such as metal foams [35–38]. The other approach entails utilization of free-form enhancers ranging from fine particles [39–44] to nanoparticles [45–55]. Khodadadi and Hosseinzadeh [45] were the first to report on the improved functionality of nanostructure-enhanced PCM (NePCM) through dispersion of nanoparticles. They simulated the solidification of a nanofluid (water with nano-size copper particles) in a square storage model. Chintakrinda et al. [46] tested the thermal performance and energy storage capabilities of an organic paraffin wax (melting temperature of 54 °C) and compared the performance of three different TCE designs. The TCE were graphite nanofibers (GNF) suspension with 11 wt% with a diameter of 50–100 nm and length of 50 μm, graphite foam with a pore diameter of 350 μm, and aluminum foam with the mean pore size of 500 μm. The boundary condition is a constant heat flux applied on the horizontal bottom base and a constant temperature cold plate on the top surface. It was found that the selection of the enhancement method had a significant effect on the thermal response of the system. Wu et al. [48] investigated experimentally the melting/freezing characteristics of paraffin by adding Cu nanoparticles. The results indicated that adding nanoparticles is an effective approach to enhance the phase change heat transfer of PCM. For a 1 wt% Cu/paraffin system, the melting and freezing times can be lowered by about 33.3% and 31.6%, respectively. Arasu et al. [50] carried out a numerical investigation to elucidate the performance enhancement of paraffin wax with nano-scale alumina (Al₂O₃) particles in comparison with base paraffin wax in a concentric double pipe heat exchanger. Numerical analysis indicated that the cyclic charge–discharge rates of thermal energy can be greatly enhanced using nano-PCM, as compared with base PCM. Arasu and Mujumdar [51], and Ho and Gao [55] studied numerically and experimentally, respectively, melting in a vertical square enclosure with a phase change material (*n*-octadecane) dispersed with nanoparticles (Al₂O₃) where heat was supplied

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