



# Experimental investigation on heat transfer characteristics during melting of a phase change material with dispersed TiO<sub>2</sub> nanoparticles in a rectangular enclosure



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## ABSTRACT

This paper presents an experimental investigation on the melting process of *n*-octadecane as a phase change material (PCM) with dispersed titanium oxide (TiO<sub>2</sub>) nanoparticles. Experiments were performed in a rectangular enclosure heated at constant rates from one vertical side corresponding to Rayleigh numbers in the range  $0.57 \times 10^8$ – $43.2 \times 10^8$  and Stefan number in the range 5.7–23.8. The rheological behavior of liquid PCM/TiO<sub>2</sub> at the mass fractions of 2 and 4% tended to Bingham fluids, thus the melting experiment was conducted for Bingham numbers in the range 0–31.1. Heat transfer during melting was characterized by visualizing the solid-liquid interface as well as recording the temperature distribution in the enclosure. Experimental results showed that at the initial stage of melting, heat transferred by conduction, and at later times, natural convection dominated heat transfer. Dispersing TiO<sub>2</sub> nanoparticles led to increase in Bingham number and consequently the natural convection and melting rate deteriorated. Two correlations were proposed to predict the Nusselt number and melted volume fraction as a function of Fourier number, Rayleigh number, Stefan number, Bingham number and mass fraction of nanoparticles.

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## 1. Introduction

A comprehensive study on heat transfer associated with melting and solidification processes is required to design an efficient latent heat thermal energy storage system. In this storage method, a large amount of thermal energy can be stored in the form of latent heat during melting process of a phase change material (PCM) and released during its solidification. This solid-liquid phase change phenomenon nearly occurs in a narrow temperature range. These favorable properties make PCMs promising for heating and cooling in various applications including transient thermal management of electronics [1,2], solar thermal storage [3,4], thermal comfort in buildings [5,6], refrigerators [7] and food transport [8]. The major disadvantage of PCMs has been the low thermal conductivity, especially in the case of paraffin waxes, leading to increase in thermal resistance near the heat transfer surface during phase change of PCM and consequently decrease in the surface heat flux. To overcome this issue, several techniques have been

proposed and investigated to promote the performance of thermal energy storage units. These methods enhance heat transfer rates and usually change the behavior of the melting or solidification process. Some of the most recent studies include effect of fins on melting rate of PCM, natural convection and melt front evolutions [9–11], increasing conduction heat transfer in PCMs by incorporating porous matrices [12,13], using heat pipes to enhance phase change rate by increasing effective conductivity [14–16].

Phase change materials with dispersed nanostructured materials as highly conductive particles have received considerable attention in recent years. The advantages of PCMs containing nanostructured materials compared to conventional performance enhancement methods include their lighter weight, no contact heat transfer issues, availability of natural convection to enhance heat transfer during melting, and their easy recycling [17]. To investigate heat transfer characteristics during melting and solidification of a PCM dispersed with nanostructured material, it is necessary to know about their thermal and rheological properties and their dependency on temperature or particle fraction. Evaluation of the thermal properties of PCMs dispersed with nanostructured materials has received significant attention in literature [18–23].

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**Nomenclature**

$A$	heat transfer area ( $\text{m}^2$ )	$x$	horizontal distance (mm)
$Bn$	Bingham number	$y$	vertical distance (mm)
$C_p$	specific heat ( $\text{J/kg}\cdot\text{K}$ )	<i>Greek symbols</i>	
$E$	electric potential (volt)	$\alpha$	thermal diffusivity ( $\text{m}^2/\text{s}$ )
$Fo$	Fourier number	$\beta$	thermal expansion coefficient of liquid ( $\text{K}^{-1}$ )
$g$	gravitational acceleration ( $=9.806 \text{ m/s}^2$ )	$\lambda$	latent heat of fusion ( $\text{J/kg}$ )
$h$	convective heat transfer coefficient ( $\text{W/m}^2\cdot\text{K}$ )	$\mu$	dynamic viscosity ( $\text{Pa}\cdot\text{s}$ )
$H$	height of the enclosure (mm)	$\mu_B$	plastic viscosity ( $\text{Pa}\cdot\text{s}$ )
$I$	electric current (amp)	$\rho$	density ( $\text{kg/m}^3$ )
$k$	thermal conductivity ( $\text{W/m}\cdot\text{K}$ )	$\tau_Y$	yield stress (Pa)
$L$	length of the enclosure (mm)	$\phi_m$	nanoparticle mass fraction
$m$	mass (g)	$\phi_v$	nanoparticle volume fraction
$Nu$	Nusselt number	<i>Subscripts</i>	
$Pr$	Prandtl number	C	cold
$q''$	heat flux ( $\text{W/m}^2$ )	H	hot
$R$	electric resistance (ohm)	l	liquid
$Ra$	Rayleigh number	m	melting point
$Sc$	Subcooling parameter	NP	nanoparticle
$Ste$	Stefan number	PCM	phase change material
$t$	time (s)	s	solid
$T$	temperature ( $^\circ\text{C}$ )	w	wall
$\Delta T$	temperature difference ( $=T_w - T_m$ )	0	initial
$V/V_0$	melted volume fraction		
$w$	uncertainty		
$W$	width of the enclosure (mm)		

The melting process is inherently complicated due to the moving solid-liquid interface and existence of natural convection heat transfer in melted region. Hence, this study is focused on the effects of dispersing nanoparticles on melting heat transfer of a PCM. There are some studies related to the melting heat transfer in PCMs containing nanostructured materials. The melting of paraffin wax dispersed with  $\text{Al}_2\text{O}_3$  particles that was heated from one side of an enclosure was investigated numerically by Arasu and Mujumdar [24]. They showed a significant degrading in natural convection heat transfer with the concentration of nanoparticles across the melted region. Hosseinizadeh et al. [25] numerically studied transient unconstrained melting of nano-enhanced phase change materials (NEPCM) inside a spherical container using RT27 as PCM and copper nanoparticles. By computing liquid fraction of NEPCM in the sphere, the results showed an enhancement of melting rate of NEPCM with respect to conventional PCM due to the increase in thermal conductivity and the lowering of latent heat of fusion. Melting process of water as PCM and copper nanoparticles in a cylindrical and rectangular cavity was computationally investigated by using Lattice Boltzmann method in Refs. [26,27]. Ho and Gao [28] performed melting experiments in a vertical square enclosure with *n*-octadecane dispersed with  $\text{Al}_2\text{O}_3$  nanoparticles. The effect of dispersing nanoparticles in the base PCM on the melting heat transfer characteristics in the enclosure was examined for the relevant parameters including mass fraction of nanoparticles, Rayleigh number, Stefan number, and subcooling parameter. They reported that a reduction of more than 60% in the quasi-steady Nusselt number arises from the nano-PCM containing 10 wt.% of alumina nanoparticles. Multi-walled carbon nanotubes (CNTs) were dispersed in 1-dodecanol to prepare NEPCM by Zeng et al. [29]. It was experimentally shown that melting is decelerated by dispersing the CNTs as a result of the dramatically increased viscosity, leading to significant degradation of natural convection during melting. Dhaidan et al. [30] studied melting of *n*-octadecane dispersed with CuO nanoparticle in a square enclosure with a constant heat flux

on one side both experimentally and numerically. Their experiments and computed results on the velocity field, shape and progress of the melting front, and evolution of melt region revealed that as the mass fraction of nanoparticles increases, the melt fraction increases, and the progress of melting interface becomes faster due to the improvement of thermal conductivity. The same authors reported the similar experimental and numerical investigation on melting of an *n*-octadecane containing CuO nanoparticles in a horizontal cylindrical capsule [31] and an annular container [32] subjected to a constant heat flux boundary condition. Transient heat transfer during melting of 1-tetradecanol/graphene composite PCMs in a bottom-heated cavity was investigated experimentally by Fan et al. [33]. An enhancement of 100% in thermal conductivity was observed along with 10 times increment in dynamic viscosity at 3 wt.% of graphene nanoplatelets. It means the enhanced heat conduction had dominant effect in melting process. The instantaneous melt fraction and heat transfer was correlated to the  $Fo$ ,  $Ste$ , and  $Ra$  numbers with an uncertainty below  $\pm 20\%$ . Fan et al. [34] conducted an experimental study to assess the problem of unconstrained melting of NePCM in a spherical container using 1-dodecanol ( $\text{C}_{12}\text{H}_{26}\text{O}$ ) as an organic PCM and Graphite nanosheets (GNSs). During unconstrained melting, the unmelted solid PCM is allowed to sink to the bottom of the sphere due to the density difference between solid and liquid phases. This phenomenon leads to the formation of close-contact melting between the bottom of the solid PCM and the internal surface of the spherical container. During unconstrained melting, the solid PCM sinks and melting at the bottom half accelerates due to the heat conduction at the lower part of the solid PCM. By undesirable dramatic growth in viscosity of molten NePCM versus improvement in thermal conductivity, the squeezing effect was weakened and the conductive molten layer was thickened. Generally, they demonstrated the utilization of NePCM was to decelerate the melting because of the effects of both thickened molten layer for close-contact melting as well as significantly suppressed natural convection.

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