

Does nanoparticles dispersed in a phase change material improve melting characteristics?



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ABSTRACT

Nanoparticles dispersed in a phase change material alter the thermo-physical properties of the base material, such as thermal conductivity, viscosity, and specific heat capacity. These properties combined with the configuration of the cavity, and the location of the heat source, influence the melting characteristics of the phase change material. In this paper, an assessment of the influence of the nanoparticles in the base material subjected to a heat generating source located in the center of an insulated square cavity, which is a common configuration in thermal capacitors for temporal heat storage is investigated. The interplay between heat conduction enhanced due to an increase in thermal conduction and buoyancy driven heat convection damped by the increase in viscosity of nanoparticles dispersed in the phase change materials is studied with the calculated streamlines and isotherms. We observed three regimes during the melting process, first at an early time duration dominated by heat conduction, later by buoyancy driven convection till the melting front levels with the center of the cavity, and lastly once again heat conduction in the bottom portion of the cavity. During the first two regimes, addition of nanoparticles have no significant performance gain on the heat storage cavity, quantified by maximum temperature of the heat source and average Nusselt number at the faces of the heat source. In the late regime, nanoparticles provide a slight performance gain and this is attributed to the increase in the specific heat of the melt due to the nanoparticles.

1. Introduction

Thermal capacitors consisting of materials with a solid to liquid phase change provides an excellent opportunity to bridge the cooling supply and demand needs, and therefore reduce the size of the thermal circuitry. Several researchers explored this idea in the context of heat storage, electronics cooling and many other applications [27,19,14,5]. These thermal management problems can be broadly divided into two categories based on the driving source, 1) temperature, 2) heat flux. An example of temperature driven application is the temporal storage of solar heat, where the temperature of heat generating part is fairly constant, as well as heat transport with heat pipes, where the condenser operates at a narrow temperature range depending on the working substance in the heat pipe [18,15,21]. The second case, is when the heat storage material has to suppress thermal runaway or dampen the temperature rise of a device, such as in electronics cooling. In case of a heat flux driven thermal storage, one key parameter of interest is the maximum temperature rise of the device [12,25].

Paraffin based materials are commonly used in terrestrial and space

applications to control the temperature of the devices around room temperature. These thermal capacitors consist of series of paraffin packed pockets with the heat generating part at the center, as shown in Fig. 1. Initially most designers have employed pure conduction models for design analyses, without considering convection during melting. The role of buoyancy driven convection was later identified to play a major role in the melt of a phase change material [9]. In a cavity with heat source at the center, the upper and the side regions surrounding the heat source have the right temperature boundary conditions for the onset of buoyancy driven flow (see Fig. 1), whereas at the bottom section below the heat source, buoyancy drive flow cannot develop.

In order to increase the thermal diffusivity of the cavity, nanoparticles mixed with phase change materials (NePCM) have been recently proposed. The main hypothesis for proposing this mixture, is that the average thermal conductivity of the substance increase, thereby increasing the overall melting process, increasing the liquid fraction, and thus reduces the maximum device temperature for a certain heat generation rate. The increase in the viscosity in the liquid phase due to the presence of nanoparticles, dampen the buoyancy driven convective

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Nomenclature

b	enthalpy-porosity coefficient, $\text{kg m}^{-3} \text{s}^{-1}$
B	dimensionless enthalpy-porosity coefficient
B_z	Boltzmann constant
c	specific heat, $\text{J kg}^{-1} \text{K}^{-1}$
f	liquid fraction
g	gravity, ms^{-2}
h	enthalpy, $\text{J kg}^{-1} \text{K}^{-1}$
L, l	cavity and heat source dimension, m
k	thermal conductivity, $\text{Wm}^{-1} \text{K}^{-1}$
Nu	Nusselt number, $-k_{nf}/k_f(T_s - T_m)\partial T/\partial n$
p	pressure, Nm^{-2}
P	dimensionless pressure
Pr	Prandtl number, $\text{Pr} = \nu_f/\alpha_f$
q'''	heat generation rate, W/m^3
Ra	Rayleigh number, $g\beta_f q''' l^5/\nu_f \alpha_f k_s$
Ste	Stefan Number, $c_f q''' l^2/h_{nf} k_s$
T	temperature, K
T_m, T_s	melting and solidification points, K
T_h, T_c	hot and cold temperatures, K
t	time, s
u, v	velocity in the x, y direction, ms^{-1}
U, V	dimensionless velocity
x, y	Cartesian coordinate, m
X, Y	dimensionless Cartesian coordinate

Abbreviations

CLF	cavity liquid fraction
PCM	Phase Change Material
NePCM	Nano enhanced PCM

Greek symbol

α	thermal diffusivity, $\text{m}^2 \text{s}^{-1}$
β	expansion coefficient, K^{-1}
μ	dynamic viscosity, N s m^{-2}
ν	kinematic viscosity, $\text{m}^2 \text{s}^{-1}$
θ	dimensionless temperature
ρ	density, kg m^{-3}
ϕ	volume fraction
σ	electrical conduction, S m^{-1}
τ	dimensionless time

Subscript

f, s	fluid and solid
m	melting point
nf	fluid PCM with nanoparticles
ns	solid PCM with nanoparticles
np	nanoparticles

currents, and therefore reduces the overall heat transfer. Therefore, when designing a nanoparticle enhanced phase change material thermal capacitor, the interplay between the increase in the thermal conductivity and decrease in convection should be carefully considered [18,15,21].

Arasu and Mujumdar [2] studied melting of paraffin wax mixed with alumina nanoparticles of a number of volume fractions, in a square cavity of side 25 mm, heated from a vertical side (see Fig. 2(a)) and in a different configuration where the cavity is heated from the bottom side (see Fig. 2(b)). The results suggest that the addition of nanoparticles decreases the melting rate of the PCM, and they conclude that the melting rate and the thermal energy storage is greater for vertical

heating, compared to horizontal heating configuration. However, compared to the base PCM, the NePCM showed a lower melting rate for both the configurations. In water based nanofluid melting, Feng et al. [8] observed a completely different trend for a bottom heating configuration, in which the melting rate increased with the volume fraction of copper oxide nanoparticles. Similar findings were reported albeit for solidification (see Fig. 2(c)) by Khodadadi and Hosseinzadeh [13] for water and copper oxide NePCM.

A concentric cylindrical configuration as shown in Fig. 2(d) is used by Dhaidan et al. [7] to investigate melting of n-octadecan mixed with copper oxide nanoparticles. The experimental results show that the melting rate decrease with an increase in volume fraction of nanoparticles. However, the maximum temperature of the wall during melting reduced with increasing volume fraction of nanoparticles. The authors suggested an eccentric configuration of the cylinders to utilize enhanced melting on the top section of the annulus. A similar configuration but a constant temperature boundary conditions as shown in Fig. 2(e) is investigated by Sebti et al. [20], with similar conclusions. In another work, Dhaidan et al. used a square enclosure with heat flux boundary conditions on one vertical side and the remain sides are insulated, as shown in the Fig. 2(f). Contrary to the findings of Arasu and Mujumdar [2] mentioned earlier, the results presented for this configuration showed that higher melting rate are possible as the volume fraction of the nanoparticles are increased.

The above discussion of the previous work point that the merits of NePCM should be discussed in the context of a particular configuration combined with the appropriate heating boundary condition pertaining to an application. The geometry shown in Fig. 1, has combined features of configuration shown in Fig. 2(a) and (b), and immediate conclusions cannot be drawn by combining the results. In this paper, a systematic numerical approach is presented to assess the addition of nanoparticles in the phase change material for the geometry and boundary conditions shown in Fig. 1. The transient flow and temperature is evaluated and the corresponding macroscopic variables such as average melt temperature, temperature of the heat source, average Nusselt number and cavity liquid fraction (CLF) are determined.

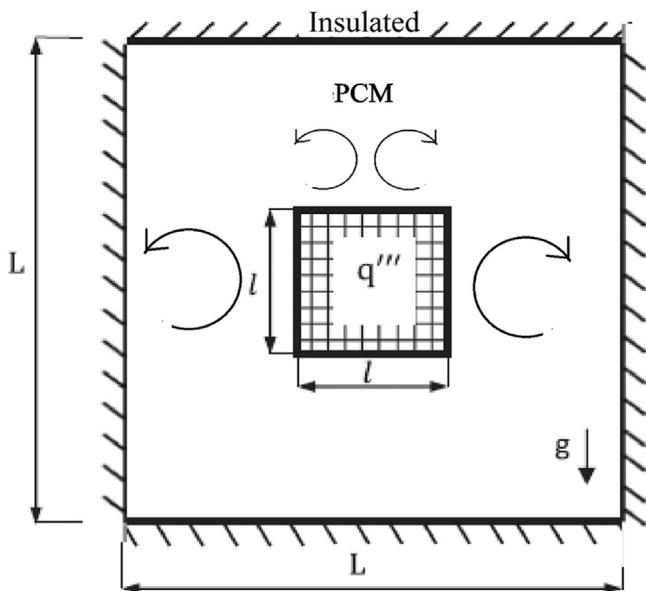


Fig. 1. Physical model of the cross-section of a heat storage cavity with heat source at the center and insulated at the outside walls.

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