

MELTING DRIVEN NATURAL CONVECTION IN NANO PCM HEATED FROM BELOW

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ABSTRACT: A two-dimensional numerical model was developed to analyze heat transfer behavior of PCM-based heat sink using Copper nano enhanced PCM. It found that the presence of CuO nanoparticles accelerates the melting of PCM and the heat source can be cooled efficiently. However, the period of safe operation of heat source decreases with increasing nanoparticles fractions.

Keywords: Nanoparticles, PCM, Latent heat storage, Thermal control, Natural convection, Heat source.

1. INTRODUCTION

Phase Change Materials (PCMs) are used to absorb and release thermal energy during transient heating and cooling. When phase change process occurs, the melting front moves away from the heat transfer surface. The surface heat flux decreases with respect to time, due to the increasing thermal resistance of the growing layer of molten medium, as the thermal conductivity of the ordinary PCM is low. Dispersing metallic nanoparticles in PCM can contribute to the improved heat transfer between the heat sink and the source [3]. Afrouzi and Farhadi [1] investigated mixed convection in a cavity filled with Cu–water nanofluid using a cubical heater located inside the cavity in different positions. They found an enhancement in heat transfer with the increase of nanoparticle volume fraction. Eastman et al. [2] showed that an increase in thermal conductivity of approximately 60 % can be obtained for a nanofluid consisting of water and 5 % Cu nanoparticles. This is attributed to the increase in surface area due to the suspension of nanoparticles. The present study simulates the melting of Nano enhanced CuO PCM, heated from below by protruding heat source mounted on not isothermal plate. The Brownian motion is taken into account to estimate the thermal conductivity of the mixture. The cooling capability of nano PCM and melting dependency on nanoparticles fraction are analyzed.

2. MATHEMATICAL MODELING

Fig. 1 presents the physical model. It consists of a horizontal rectangular enclosure containing a copper nano enhanced PCM (CuO, n-eicosane, $T_m = 47$ °C), heated with protruding heat source attached to the conducting plate (bottom wall). The height and thickness of heat source are $L_c = 3$ cm and $X_c = 0.5$ cm, respectively. The height and width of the enclosure are, $H_m = 10$ cm, and, $L_m = 10$ cm, respectively. The thickness of the conducting plate is, $X_s = 0.5$ cm. Heat source generates heat at constant and uniform rate, $Q' = 80$ W/m, and dissipates that heat through their exposed faces to the plate and PCM. All enclosure boundaries are adiabatic. Nano PCM including nanoparticles and base fluid as continuous media is Newtonian, incompressible, and assumed to be in thermal equilibrium as well as no slip condition is imposed between them. The momentum field is subjected to no-slip boundary conditions at the solid walls. The flow is two-dimensional, laminar. Effective

thermal conductivity depends on particle size, particle volume fraction and temperature as well as properties of the base PCM and the particle is subject to Brownian motion. The physical properties of the materials, except thermal conductivity, are constant at the temperature range under study. The Boussinesq approximation is used in the momentum equation for the vertical direction.

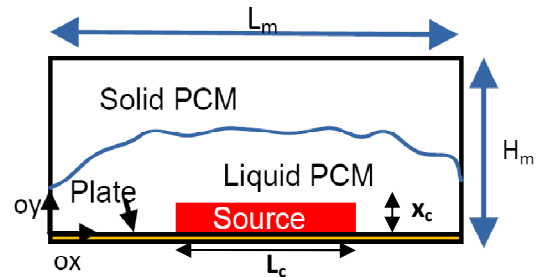


Fig. 1: The physical model

- Governing equations

The general equation governing heat, mass transfer and flow in the studied configuration is as follows:

$$\frac{\partial(\rho\Omega)}{\partial t} + \frac{\partial(\rho u\Omega)}{\partial x} + \frac{\partial(\rho v\Omega)}{\partial y} = \frac{\partial^2(\Gamma\Omega)}{\partial x^2} + \frac{\partial^2(\Gamma\Omega)}{\partial y^2} + S_\Omega \quad (1)$$

Terms of Eq. (1) are summarized in the Table 1.

Table 1: Terms of the general equation

Ω	Γ	S_Ω
1	0	0
U	μ	$-\frac{\partial p}{\partial x} + S_u$
V	μ	$-\frac{\partial p}{\partial y} + S_v$
H	k/c_p	S_T

$$\text{here, } \begin{cases} H = \int_{T_m}^T c_p dT + h(T_m) \\ S_u = -C \frac{(1-f)^2}{(f^3+b)} u \\ S_v = -C \frac{(1-f)^2}{(f^3+b)} v + (\rho\beta)_{nf} g(T - T_m) \\ S_T = \delta_1 \left(-(1-\delta_2)\rho_{nf}\Delta H_f \frac{\partial f}{\partial t} + \delta_2 \frac{Q'}{X_c L_c} \right) \end{cases} \quad (2)$$

S_u and S_v are source terms for the velocity suppression in the solid regions using a Darcy-like term [4] ($C = 10^{25}$ kg m⁻³s⁻¹ and $b = 0.005$). The conductivity k and the step function δ are as follows:

$$\delta_1 = \begin{cases} 1 & \text{heat source, PCM} \\ 0 & \text{plate} \end{cases}, \delta_2 = \begin{cases} 1 & \text{heat source} \\ 0 & \text{PCM} \end{cases} \quad (3)$$

$$k = \begin{cases} k_{eff} & \text{PCM} \\ k_s & \text{plate} \\ k_c & \text{heat source} \end{cases} \quad (4)$$

The effective thermal conductivity of the nanofluid k_{eff} for spherical nanoparticles, subject to Brownian motion, according to Maxwell [5,6] is:

$$k_{eff} = \frac{k_p + 2k_m - 2\Phi(k_m - k_p)}{k_p + 2k_m + \Phi(k_m - k_p)} k_m + 5 \times 10^4 \beta f \phi \rho_m C_{p,m} \sqrt{\frac{BT}{\rho_p d_p}} F(T, \phi) \quad (5)$$

where B is Boltzmann constant $1.381 \times 10^{-23} \text{J/K}$, and

$$\left\{ \begin{array}{l} \beta = 8.4407(100\phi)^{-1.07304} \\ F(T, \phi) = (2.8217 \times 10^{-2} \phi + 3.917 \times 10^{-3}) \frac{T}{T_m} + (-3.0669 \times 10^{-2} \phi - 3.91123 \times 10^{-3}) \end{array} \right. \quad (6)$$

The second part of Eq. 5 accounts for Brownian motion, which causes the temperature dependence of the effective thermal conductivity. Note that liquid fraction, f is used as correction factor in the Brownian motion term, since there should be no Brownian motion in the solid phase.

The dynamic viscosity of the nanofluid, for small particles fraction, Φ , given by Einstein [7]:

$$\mu_{nf} = (1 + 2.5\Phi) \mu_m \quad (7)$$

Different physical properties of materials are expressed as follows [8]:

$$\begin{aligned} (\rho\beta)_{nf} &= \Phi(\rho\beta)_p + (1-\Phi)(\rho\beta)_m, \\ (\rho c_p)_{nf} &= \Phi(\rho c_p)_p + (1-\Phi)(\rho c_p)_m, \\ \rho_{nf} &= \Phi \rho_p + (1-\Phi) \rho_m, \quad k_i = \frac{k_+ k_- (\delta_+ + \delta_-)}{k_+ \delta_- + k_- \delta_+} \end{aligned} \quad (8)$$

δ_+ and δ_- are distances separating the interface to the first neighboring nodes, '+' and '-', k_+ and k_- are the thermal conductivities at nodes '+' and '-', respectively.

- Boundary conditions

At the interfaces between two different materials (1) and (2) (plate, PCM or heat source):

$$k_1 \frac{\partial T}{\partial \eta} \Big|_{interface} = k_2 \frac{\partial T}{\partial \eta} \Big|_{interface}, \quad T_1 = T_2 \quad (\eta \perp \text{ interface}) \quad (8)$$

At the adiabatic walls:

$$\frac{\partial T}{\partial \eta} \Big|_{wall} = 0 \quad (9)$$

No slip and no permeability at the solid interfaces and walls:

$$u = v = 0 \quad (10)$$

The local liquid fraction f is determined iteratively from the solution of the enthalpy equation as:

$$\left\{ \begin{array}{ll} f = 1 & \text{if } T > T_m \\ f = 0 & \text{if } T < T_m \\ 0 < f < 1 & \text{if } T = T_m \end{array} \right. \quad (11)$$

- Initial conditions

$$u = v = f = 0, \quad T = T_m \quad (12)$$

The governing equations are discretized using a finite volume method [8] and an optimized 120X60 mesh was used. The resulting algebraic equations are solved, for every time step, using the Tri-Diagonal Matrix iterative method. The pressure and velocity coupling is treated by SOR algorithm. The model was implemented in a personal code using C++ language.

3. RESULTS AND DISCUSSION

Fig. 2 shows the time wise evolution of maximum heat source temperature, T_{max} , and total liquid fraction, f , for various nanoparticles fractions, $\Phi=0\%$, 0 %, 1%, 2 % and 3%. Numerical investigations were performed using Table 2.

Table 2: Physical properties [2,9]

Heat source	Conducting Plate
$\rho_c = 3260 \text{ kg/m}^3$	$\rho_s = 1188 \text{ kg/m}^3$
$c_{p,c} = 740 \text{ J/kg K}$	$c_{p,s} = 1445 \text{ J/kg K}$
$k_c = 170 \text{ W/m K}, T_{cr} = 80 \text{ }^\circ\text{C}$	$k_s = 0.193 \text{ W/m K}$
Nanoparticles (CuO-Copper)	PCM (n-eicosane)
$\rho_p = 8933 \text{ kg/m}^3$	$\beta = 8.5 \times 10^4 \text{ K}^{-1}$
$c_{p,p} = 385 \text{ J/kg K}$	$\Delta H_f = 2.47 \times 10^5 \text{ J/kg}$
$k_p = 400 \text{ W/m K}$	$T_m = 47 \text{ }^\circ\text{C}$
$d_p = 60 \text{ nm}$	$c_{p,m} = 2460 \text{ J/kg K}$
	$k_m = 0.1505 \text{ W/m K}$
	$\rho_m = 769 \text{ kg/m}^3$
	$\mu_m = 4.15 \times 10^{-3} \text{ kg/m s}$

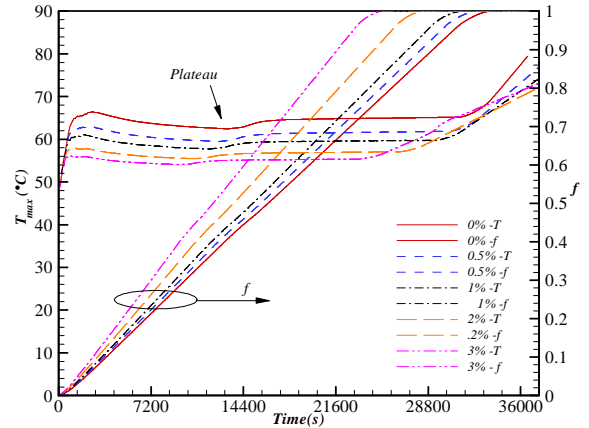


Fig. 2: Maximum heat source temperature, T_{max} , and total liquid fraction, f , for various nanoparticles fractions, Φ .

Analysis of Fig. 2 shows that heat source temperature vary within 3 stages whatever the nanoparticles fraction is. At the first stage, heat source starts the melting of a thin layer of PCM. Temperature difference between the source faces and the melting front is still weak that heat transfer occurs essentially by heat conduction in liquid PCM. With time progress, heat source evacuates more energy in vicinity PCM and the maximum temperature rises rapidly due to the weak value of thermal conductivity of PCM, ($k_m = 0.1505 \text{ W/mK}$, $\Phi=0$). Note that, during the first stage of melting process, heat source maximum temperature rises rapidly to $67 \text{ }^\circ\text{C}$ for ordinary PCM but increases only to $56 \text{ }^\circ\text{C}$ for PCM with 3 % of copper nanoparticles. As time elapses, the liquid cavity enlarges, (because of space limitation figure is note presented), and the driven temperature between the melting front (moving cold wall) and the bottom hot wall increases and initiates the liquid motion within the liquid phase and the heat transfer turns into natural convection. Hot and light liquid rises over the heat source and returns along the cold melting front, the liquid release it heat and becomes cooled and heavier,

descends and turns over to the bottom wall and re-absorbs more heat from heat source, The maximum temperature decreases sharply from 67°C to 63°C for ordinary PCM and from 56°C to 54°C for PCM with 3% copper nanoparticles. A pseudo steady state regime takes place. During the plateau region, heat source maximum temperature is kept even constant, sensible heating disappears and all generated energy by heat source is absorbed by the melting front as latent heat storage. Liquid fraction increases with time and raises rapidly with higher nanoparticles concentrations (Fig. 2). The melting front (the cold wall) travels far from heat source. During the plateau period, heat source is efficiency cooled and works a long period without using any forced convection fans. Also, Fig. 2 shows that the plateau period length decreases clearly with nanoparticle fraction. In fact, heat source works safely during, $t_{plateau} = 8$ hours and 45 minutes for base PCM and, $t_{plateau} = 6$ hours and 40 minutes for PCM with 3% CuO particles. In fact, when adding more nanoparticles to base PCM, heat conduction is adorned, and the source evacuates it heat easily to PCM, and provokes fast fusion. The last stage of the melting process sets up when heat source reheats. In fact, thermal resistance of liquid cavity rises and liquid phase near heat source overheats to critical temperature, T_{cr} , depending on nanoparticles fraction. During the third stage, the complete melting of PCM gives a situation of heat source without heat sink (no cold boundaries) and heat source overheats. It's worthy to notice that, depending to the electronic component (heat source) working conditions and sensitivity, there is a duality between working with lowest temperature during a court plateau period for more concentrated nanoPCM or with even high temperature during lager plateau period for low particles fraction as can be seen in Fig. 2.

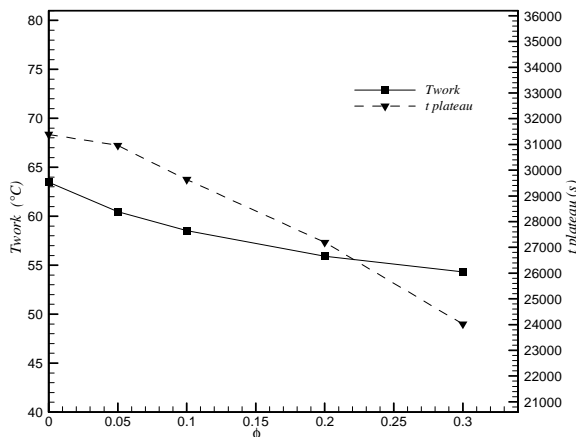


Fig. 3: Maximum heat source temperature and secured working time during the plateau stage.

Analysis of Fig. 3 substantiates the doubt concerning the effective enhancement in the PCM cooling performance due to dispersing the nanoparticles, relative to the simple PCM. The effective thermal conductivity improvement could be outweighed by the rise in the dynamic viscosity. Also, heat sinking capability, for a given PCM enclosure size, depends closely to the particles volumetric fractions. The maximum amount of energy that can be dissipated in PCM decreases with the increase of the added particles. That reduces the volume occupied by the base PCM. Also the increase in dynamic viscosity will extinguish the role of natural convection with the excess of nanoparticles across the melted region. And as mentioned above, the damping convection current creates a near isothermal homogeneous liquid. Therefore, there is an optimal volumetric fraction of nanoparticles, to be added, which exhibits lower working temperature with adequate working time. Based on Fig. 3 data, the working temperature,

T_{work} and the secured working time, $t_{plateau}$ are correlated to the nanoparticle fraction by equations Eq. 13 and Eq. 14, with accuracy 8% and 5%, respectively.

$$T_{work} = -29.2 \Phi + 62.3 \quad (^\circ\text{C}), \quad 0 \leq \Phi \leq 0.03 \quad (13)$$

$$t_{plateau} = -7 \Phi + 8.87 \quad (\text{hr}), \quad 0 \leq \Phi \leq 0.03 \quad (14)$$

4. CONCLUSION

In this study, the effect of copper nanoparticles fraction on cooling capability of protruding heat source embedded PCM is numerically investigated. Results reveal that the increment of volume fraction of nanoparticles causes more stability of heat source temperature during the plateau region. An increase in nanoparticles from, 0% to 3%, leads to improved heat spreading within the liquid phase, as is indicated by enhancement in working temperature that reduced from 67°C to 55°C. However, the increase in particles fraction shifts convection currents, reducing the time it takes the PCM to melt completely and decreases the secured working time.

NOMENCLATURE

d_p	nanoparticle diameter, m
F	liquid fraction
h	enthalpy, J kg ⁻¹
H_m	height of the enclosure, m
L_c	heat source length, m
L_m	width of the enclosure, m
Q'	heat source generation per unit length, W m ⁻¹
S	source term
u, v	x, y velocity, m s ⁻¹
X_c	heat source thickness, m
X_s	substrate (plate) thickness, m

Greek symbols

β	volumetric thermal expansion factor of liquid PCM, K ⁻¹
ν	cinematic viscosity, m ² s ⁻¹
ρ	density, kg/m ³
ΔH_f	latent heat, J kg ⁻¹

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