Investigation of Property Variations on Freezing of PCM Containing Nanoparticles

[1,2]M.Y. Abdollahzadeh Jamalabadi and [2,3]Jae Hyun Park

[1]Chabahar Maritime University, Iran
[2]Department of Aerospace and System Engineering
[3]Research Center for Aircraft Parts Technology,
Gyeongsang National University, Jinju, Gyeongnam 660-701, South Korea

Abstract: Improvement of thermal and heat transfer capabilities of phase change materials with adding nanoparticles were reported. The resulting phase change materials display superior thermal conductivity and density and lower heat capacity and latent heat, in comparison with the base material. The purpose of this paper is to present the effect of adding nanoparticles on thermophysical properties of PCM and applying it in one engineering case. So a transient natural convection within a differentially-heated square cavity that contains a nanofluid was considered. To solve the governing nonlinear differential equations a code based on finite volume method is developed and utilized. The nanofluid was allowed to undergo solidification. The predicted increase of the heat release rate and solidification of the phase change materials is shows its great potential for temperature control applications. Furthermore through transient condition, the convection heat transfer overcomes the conduction heat transfer. By adding nano-particles the transition from conduction heat transfer regime to convection heat transfer regime occurs in sooner times.

Key words: Nano-particles · Nanofluids · Phase change · Temperature control · Natural convection · Solidification

INTRODUCTION

Heat transfer with phase change occurs in many industrial applications. In phase change applications energy storage are most important as it arises involuntary. Use of latent heat during phase change is the aim of energy storage units. Nowadays phase change materials are used as heat sinks and controls temperature in electronic industries, communication systems, power plant boilers, greenhouse heating systems and insulation of buildings [1]. Nanotechnology with improvement of some properties of material opened a great number of chances for new technological innovations in many fields of engineering [2-5]. The idea of increasing thermal conductivity of fluid by adding fine particles is first offered by Maxwell [6]. Through the progress of nanotechnology, a modern way in enhancing thermal conductivity of heat transfer fluid is to suspend metal or metal oxide nano-particles (smaller than 100 nm) inside it. The consequential mixture referred to as nanofluids have a significantly superior thermal conductivity compared to that of base fluids [7, 8]. Several researchers have studied the enhancement of PCM's thermo-physical by adding nano-particles to the phase change materials [9-10]. Jay Khodadadi and Liwu Fan [10] employed a well-established integral/analytic technique for solving a NEPCM problem and the property variation issues were incorporated in the analysis. But it limited to one-dimensional. More recently Khodadai and Hosseinizadeh have studied the enhancement of PCM materials with nano-particle [11]. In their study, the thermo-physical effect of nano-particle is assumed to be constant in the solid and liquid domain.

The purpose of this paper is to numerically investigate the effect of nano-particles (thermo-physical properties variation) on phase change materials (PCMs) in a two dimensional cavity. In this study the properties of the enhanced PCM vary during the phase change formation. However the effect of nano-particles on fluid movement (i.e. Brownian motion) is neglected.

Problem Statement: Time dependent buoyancy-driven convection in a differentially-heated cavity containing a phase change material based nanofluid. The schematic of the problem is depicted in Figure 1. The cavity is filled
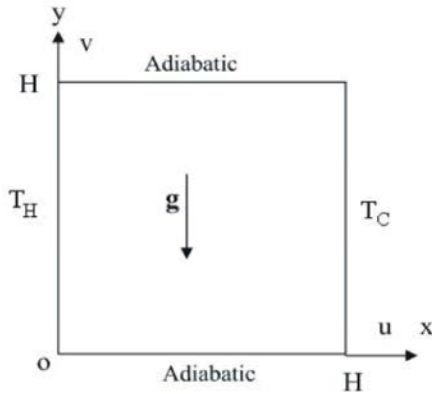
Corresponding Author: M.Y. Abdollahzadeh Jamalabadi, Chabahar Maritime University, Chabahar, Iran.

Fig. 1: Schematic of the enclosure

Table 1: Thermophysical properties of base fluid and nanoparticle [1, 11]

| | Phase change material | | |
	Solid	Liquid	Copper nano-particle
ρ	1710	1530	8954
k	1.09	0.53	400
cp	1400	2200	383
β	-	0.0002	1.67×10-5
H	187000	-	
μ	0.00533	-	

Table 2: Thermophysical properties of nanofluid

| | $\phi = 0.1$ | | $\phi = 0.2$ | |
	Solid	Liquid	Solid	Liquid
ρ	2272.4	2434.4	3158.8	3014.8
k	1.45	0.7	1.63	0.92
cp	1010.07	1503.3	806.9	1140.3
β	-	6.8×10-5	-	5.1×10-5
H	-	115303.58	-	77947
μ	-	6.9×10-3	-	9.3×10-3

with nanofluid that is a hydrated salts PCM (TH29) with solid copper nano-particles. Three solid particle volume fractions (0, 0.1 and 0.2) are considered. The associated properties of PCM and nano-particles are given in Table 1 [1]. The related thermo-physical properties of the nanofluid are given in Table 2.

Governing Equations: To come up with the governing equations the following are assumed: the nanofluid is treated as a continuous, an incompressible and Newtonian fluid. Thermophysical properties of the nanofluid are assumed to be constant, whereas the density variation in the buoyancy force term is handled by the Boussinesq approximation. The base fluid and the solid nano-particles are both at thermal equilibrium and their thermophysical properties are constant. The 2-Dimensional governing equations for the cavity are:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

X-momentum equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{nf}}\frac{-\partial p}{\partial x} + \upsilon_{nf}\nabla^2 u \tag{2}$$

Y-momentum equation:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\frac{-\partial p}{\partial y} + \upsilon_{nf}\nabla^2 v - \beta_{nf} g(T - T_{ref}) \tag{3}$$

Energy equation:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial x}[\frac{k_{nf}}{\left(\rho c_p\right)_{nf}}\frac{\partial T}{\partial x}] + \frac{\partial}{\partial y}[\frac{k_{nf}}{\left(\rho c_p\right)_{nf}}\frac{\partial T}{\partial y}] \tag{4}$$

It is impossible to estimate the effective properties of nano?uids unless all the details of their microstructures are known completely. One way to avoid this problem is to estimate the effective properties based on several reasonable assumptions on the microstructures of the mixtures. So we are using ordinary relations coming in early studies. Where density, part of the Boussinesq term and the heat capacitance of the nanofluid are given by:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s$$
$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_s$$
$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s \tag{5}$$

Density variation will also bring in complications of volume change upon phase change within a fixed volume cavity. In this paper gas release and pressure increase during ice formation have neglected. The viscosity of the nanofluid contains small rigid spherical particles and latent heat of the nanofluid is given by [3]:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}$$
$$(\rho H)_{nf} = (1-\phi)(\rho H)_f \tag{6}$$

Also the thermal conductivity is as follows [6]:

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)} \tag{7}$$

It should be noted that even given its form, Maxwell's equation is only a first-order approximation and applies only to mixtures with low particle-volume concentrations.

Enthalpy Method for PCM at Freezing Condition: The transient energy equation in phase change material is [12, 13]:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x}(\rho u h) + \frac{\partial}{\partial y}(\rho v h) = \frac{\partial}{\partial x}(k\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k\frac{\partial T}{\partial y}) \quad (8)$$

where enthalpies for PCM are:

$$\begin{cases} H_{solid\ phase} \leq C_s(T_m - T_{ref}) & if\ \ T_p < T_m \\ H_{liquid\ phase} > C_s(T_m - T_{ref}) + H_L & if\ \ T_p > T_m \\ C_s(T_m - T_{ref}) < H_{melting\ duration} < C_s(T_m - T_{ref}) + H_L & if\ \ T_p = T_m \end{cases}$$
$$(9)$$

Finally the definition of liquid fraction (ratio of PCM enthalpy to liquid enthalpy) γ is as follows:

$$\begin{cases} T < T_m \rightarrow \gamma = \dfrac{H}{H_L} = 0 \rightarrow Solid\ Phase \\ T > T_m \rightarrow \gamma = \dfrac{H}{H_L} = 1 \rightarrow Liquid\ Phase \\ T = T_m \rightarrow 0 < \gamma = \dfrac{H}{H_L} < 1 \rightarrow phase\ change \end{cases}$$
$$(10)$$

Boundary Condition: Temperature difference between the two walls is 3°C (T_H = 29°C and T_C = 26°C). Other boundary conditions are:

$$\begin{aligned} u = v = \frac{\partial T}{\partial y} = 0 & \quad at\ y = 0, H \quad and\ 0 \leq x \leq H \\ u = v = 0, T = T_H & \quad at\ x = 0 \quad and\ 0 \leq y \leq H \\ u = v = 0, T = T_C & \quad at\ x = H \quad and\ 0 \leq y \leq H \end{aligned}$$
$$(11)$$

Starting at time t=0, the temperatures of both active left and right walls are equals and the temperature of the right wall suddenly is lowered at 3°C below the freezing temperature of the base fluid. The fluid is motionless for t < 0 and upon initiation of freezing a start-up natural convection problem is implied. The PCM on the right side starts to freeze, the solid front travels to the left and the remainder of the cavity that is a liquid will experience natural convection. This set-up is different than [11] where for t < 0, natural convection was fully established. The remaining boundary conditions is unchanged in comparison with initial condition, t = 0.

Numerical Procedure: A numerical code based on SIMPLE method is utilized [14]. The governing differential equation is discritized using modified QUICK differencing scheme [15]. In order to avoid pressure fluctuations in the pressure correction equation, the Rhie-Chaw method is applied [16]. The under-relaxation factors for the velocity components, pressure correction, thermal energy and liquid fraction were 0.5, 0.3, 1 and 0.9, respectively. Time discretization takes place with the implicit Euler method. The one second time step is presumed for integrating the temporal derivatives that satisfies the Courant–Friedrichs–Lewy condition (CFL condition). Resulted implicit equations solved by alternating direction implicit (ADI) method. Maximum iteration performed in each time step is 1000 iterations. The convergence criterion for maximum residuals is 10^{-7} except for energy equation which is 10^{-9}. In this problem this convergence criteria is achieved in about 500 iterations in each time step. A structured type grid is considered for both direction (x and y) and the grids are uniformly spaced. The grid dependency is checked and is presented in Figure 3.

RESULTS

The augmentation of a differentially heated square cavity filled with PCM is investigated. The phase change material is made of high temperature hydrated salts and nano-particles (i.e., φ = 0, 0.1 and 0.2). The accuracy of the proposed numerical method has been checked with studies done by Khodadadi and Hosseinizadeh [11]. As shown in Figure 2 the solidification front for normal case show the same trend as presented by Khodadadi and Hosseinizadeh. Also The grid independency for the current study is present in Figure 3. The solution is obtained for various grid sizes, as shown by the Figure. Figure 3 shows that as the number of grid increase the resolution of solidification profile increases and converges to appropriate resolution. The resolution does not changed significantly after 150x150 grid sizes. However for assurance the results are obtained for 200x200 grid sizes. Figure 4 shows variation of PCM solidification front with time when no particles are added (i.e. φ = 0). As time increases the convection heat transfer (the thermal boundary layer thickness) overcomes the conduction of heat transfer.

Consider the thermal boundary layer thickness as the distance from the solidification front at which the temperature is 99% of the temperature difference in cavity
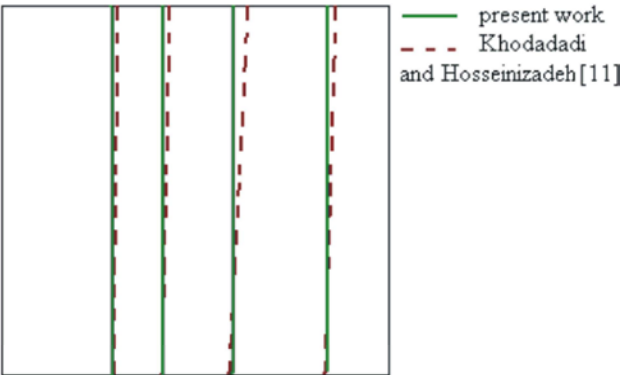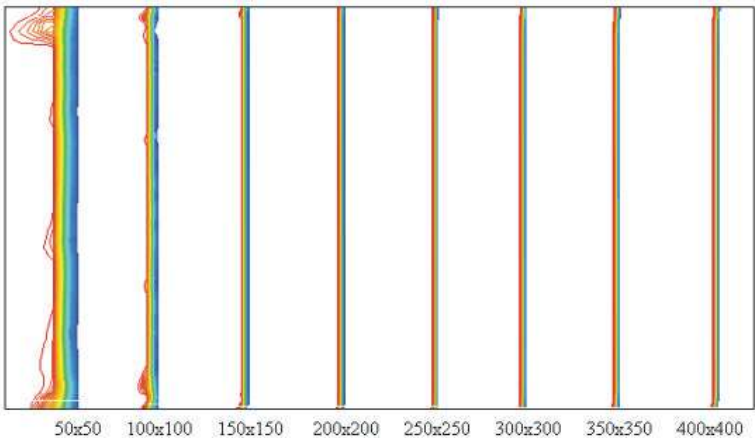
Fig. 2: Comparison of solidification front with [11]

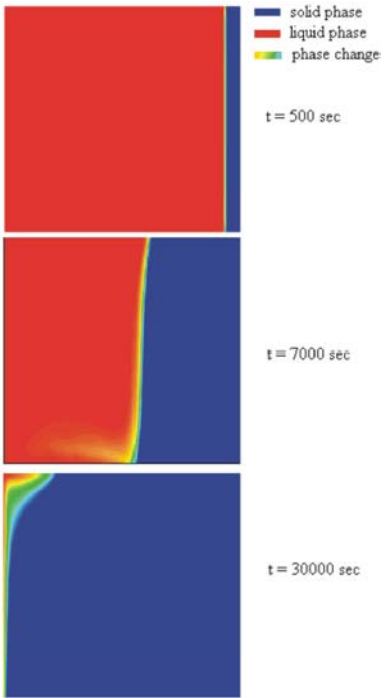Fig. 3: Phase change zone for various grid size
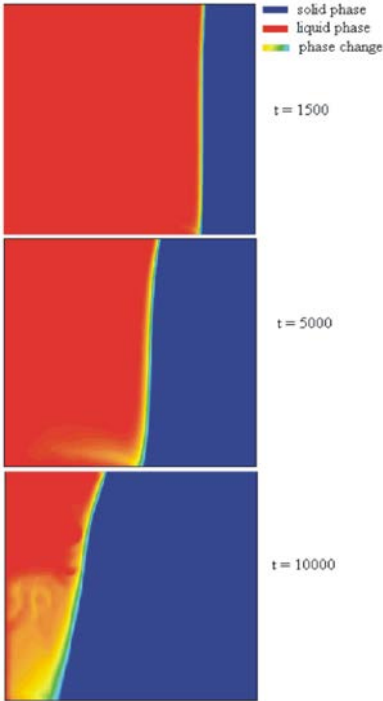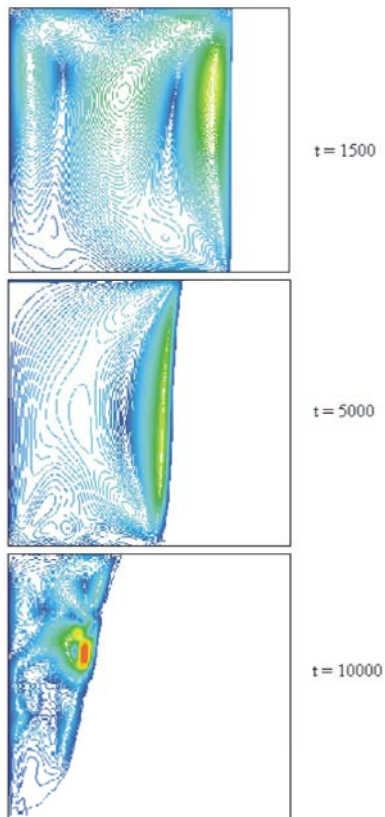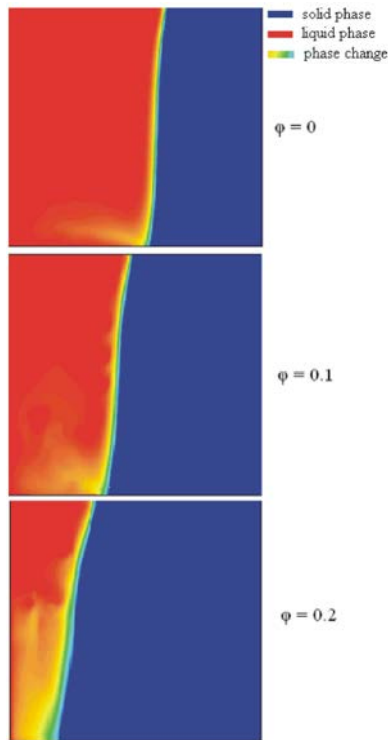

Fig. 4: Variation of PCM front with time for φ=0

Fig. 5: Variation of PCM front with time for φ=0.1

Fig. 6: Variation of velocity streamline with time for φ=0.1

Fig. 7: Variation of PCM front with particle fraction for t=10000

from melting point. Because the Prandtl number is greater than 1, the thermal boundary layer is thinner than the velocity boundary layer about solidification front that resulted from natural convection in liquid. Figures 5 and 6 show the variation of PCM solidification front and velocity streamlines with time when nano-particles volume fraction is 20% (ö = 0.2), respectively. Again as time increases the convection mode overcomes the conduction mode. That is at initial times having conduction dominated solidification and in larger time natural convection heat transfer rate is larger than conduction heat transfer rate. Deviation from a perfect vertical interface is clear from Figures 5 and 6.

Figure 7 shows the variations of PCM with nano-particles. As shown, the rate of transition from conduction to convection is faster when nano-particles are added to the PCM and therefore transition time is reduced. Furthermore, as nano-particles is added to the PCM, the region is no longer stratified.

Table 3 shows the freezing time for PCM with different volume fraction of nano-particles. As indicated by Table, freezing time reduces when nano-particle volume fraction increase (about 42%). As indicated before, the nano-particles augmented the conductive and convective properties of the PCM (i.e., thermal conductivity and the natural convection heat transfer coefficient).

CONCLUSIONS AND RECOMMENDATION

- The energy capacity of the nanofluid (PCM with nanoparticles) is lower than typical phase change materials.
- The nano-particles augment the conductive and convective properties of the PCM.
- In phase change problem the convection heat transfer overcomes the conduction heat transfer as time increases. However with nano-particles the transition from conduction heat transfer to convection heat transfer regime.
- Nano-particles are best for thermal control purposes. It is not desirable to use nano-particles as thermal storage materials.

ACKNOWLEDGEMENT

Nomenclature:

c   specific heat capacity
H   latent heat of fusion
g   gravitational acceleration
k   thermal conductivity
P   pressure
T   temperature
u,v velocity in x direction
β Thermal expansion coefficient
ρ density
γ Liquid fraction
φ volume fraction of solid particles

subscripts

m   Freezing condition
nf nanofluid
f   fluid
p   Phase change material
ref Initial condition
s   solid

REFERENCES

1. http://www.europeanthermodynamics.com.
2. Mehling, H. and L.F. Cabeza, 2008. "Heat and cold storage with PCM", Springer-Verlag Berlin Heidelberg.
3. Das, S.K., U.S. Stephen, W. Yu Choi and T. Pradeep, 2008. "Nanofluids science and technology", John Wiley & Sons.
4. Davis, S.H., 2001. "Theory of solidification", Cambridge.
5. Gupta, S.C., 2003. "The classical Stefan problem basic concepts, modeling and analysis", Elsevier.
6. Maxwell, J.C., 1954. "A treatise on electricity and magnetism" (Dover, New York, 3rd ed., 1: 435.
7. Masuda, H., A. Ebata, K. Teramae and N. Hishinuma, 1993. "Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles", Netsu Bussei, 7(4): 227-233.
8. Choi, U.S., 1995. "Enhancing thermal conductivity of fluids with nano-particles, in: developments and application of non-Newtonian flows", ASME, FED-Vol. 231/MD-V, 66: 99-105.
9. Ho, C.J. and J.Y. Gaoa, 2009. "Preparation and thermophysical properties of nanoparticle-in-paraffin emulsion as phase change material", International Communications in Heat and Mass Transfer, 36: 467-470.
10. Jay Khodadadi and Liwu Fan," 2009. Expedited Freezing of Nanoparticle-Enhanced Phase Change Materials (NEPCM) Exhibited Through a Simple 1-D Stefan Problem Formulation", ASME Summer Heat Transfer Conference, San Francisco, California (2009) Paper No: HT2009-88409.
11. Khodadadi, J.M. and F. Hosseinizadeh, 2007. "Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage", International Communications in Heat and Mass Transfer, 34: 534-543.
12. Chiu, K. and J. Caldwell, 1996. "Application of broyden's method to the enthalpy method for phase change problems", Numerical Heat Transfer, Part. A, 30: 575-587.
13. Bejan, A., 1996. "Entropy generation minimization ", CRC Press.
14. Patankar, S.V. and D.B. Spalding, 1972. "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows", International Journal of Heat and Mass Transfer, 15: 1787-1806.
15. Chen, Y. and R.A. Flaconer, 1992. "Advection-diffusion modeling using the modified QUICK Scheme", International Journal for Numerical Methods in Fluids, 115: 1171-1191.
16. Rhie, C.M. and W.L. Chow, 1983. "Numerical study of turbulent flow past an airfoil with trailing edge separation". AIAA Journal, 21(11): 1525-1532.