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A Numerical Investigation of Solidification in Horizontal Concentric Annuli Filled with Nano-Enhanced Phase Change Material (NEPCM)

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Abstract: Heat transfer enhancement during phase change is important in design of latent heat thermal energy storage system. This paper presents a numerical study of heat transfer enhancement during solidification in concentric cylindrical horizontal annulus through dispersion of nanoparticle. An enthalpy porosity technique with finite volume approach was used to trace the solid and liquid interface. The resulting nanoparticle-enhanced phase change materials (NEPCM) exhibit enhanced thermal conductivity in comparison to the base material. Water-based NEPCM containing various volume fractions of Cu nanoparticles is used. In this study, the influence of some effective parameters such as: different volume fractions of nanoparticles and temperature range are studied and discussed. It was observed that increasing nano particle volume fraction, increases the heat transfer rate then significantly reduce the total solidification time.

Key words: Nano particle · Phase change material · Solidification · Thermal energy storage

INTRODUCTION

Nowadays, due to increasing demand of energy, the renewable energy sources are particularly attractive. But the storage of energy in suitable forms is as important as developing renewable energy sources. As an example, one of the difficulty of using solar energy as a renewable energy is how to storage it during nights or whenever don't access. The latent heat thermal energy storage system using phase change materials (PCMs) is an effective method of energy storage. Because of high energy storage density and isothermal phase transition, PCMs have been widely used in latent heat thermal energy storage systems such as solar energy and spacecraft thermal control applications.

In order to develop and design an efficient and cost effective latent heat thermal energy storage system, many researchers in the past have investigated numerous problems pertinent to latent heat thermal energy storage and utilization. Zalba *et al.* [1] performed a detailed review on thermal energy storage that dealt with phase change materials, heat transfer studies and applications. Kenisarin and Mahkamov [2] presented a review of on the assessment of the thermal properties of various PCMs, methods of heat transfer enhancement and design configurations of heat storage facilities to be used as a part of different solar systems. Jegadheeswaran and Pohekar [3] reviewed the influence of enhancement techniques on the thermal response of the PCM in terms of phase change rate and amount of latent heat stored/retrieved has been addressed as a main aspect.

The drawback of this type of thermal energy storage system is that the thermal conductivity of the PCMs are usually very low and its lead to low heat transfer rates during both charging and discharging processes in the latent heat storage unit . In order to overcome this problem during such processes, using ultra fine solid particles in the base PCM are employed. The presence of the nanoparticles in the fluids increases appreciably the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics. A review of the unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity and in addition, the outline of the recent research in experimental and theoretical studies on convective heat transfer in nanofluids, is performed by Godson *et al.* [4]. Xuan and Li [5] reported experimental results on convective heat transfer for laminar and

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turbulent flow of a nanofluid inside a tube. Their results show extraordinary enhancement in heat transfer performance over the base fluid for the same Reynolds number. Moraveji *et. al* developed a new model for thermal conductivity prediction of nanofluid mixtures [6]. Khodadadi and Hosseinizadeh [7] were the first to report on improved functionality of phase change materials (PCM) through dispersion of Nano particles. They found that the resulting nanoparticle-enhanced phase change materials (NEPCM) exhibit enhanced thermal conductivity in comparison to the base material. Ranjbar *et. al.* [8] investigated the influence of utilizing Nano particle on enhancement of heat transfer in a three dimensional cavity. Khodadadi and Fan [9] utilized an analytic/integral approach to solve a model 1-dimensional Stefan problem for a Nanofluid that undergoes freezing. Their model accounts for the thermal property jumps between the liquid and solid phases and showed that the freezing time to decrease as the volume fraction of the nanoparticle is raised.There are only few published experimental data that are addressing the use of particles in order to enhance PCMs. Wu *et al* [10] developed a new sort of nanofluid phase-change material by suspending a small amount of nanoparticles in melting paraffin. They select Cu, Al and C/Cu nanoparticles add to the melting paraffin to enhance the heat-transfer rate of paraffin, Cu nanoparticles have the best performance for heat transfer. Wu *et al* [11] studied the potential of Al_2O_3-H_2O nanofluids as a new phase change material for the thermal energy storage of cooling systems. The thermal response test shows the addition of Al_2O_3 nanoparticles remarkably decreases the supercooling degree of water, advances the beginning freezing time and reduces the total freezing time. They showed that only adding 0.2 wt% Al_2O_3 nanoparticles, the total freezing time of Al_2O_3-H_2O nanofluids can be reduced y 20.5%.

In this study the solidification behavior of the NEPCM is numerically tested in a horizontal concentric annulus filled with Cu-water Nanofluid as NEPCM. Effects of nanoparticle volume fraction (ϕ = 0,0.025, 0.05) and the temperature difference (ΔT = 5, 10, 20) on solidification time and influence of natural convection is studied in details. For simulation we use small value of nanoparticle volume fraction. High values of volume fraction will make nanoparticles easier to aggregate thus at those high concentrations the Nanofluid is unstable and thus cannot be used in such a hostile environment of melting and freezing. The rest of the paper is organized as follows. In Section 2, we present problem statement and in section 3, governing equation and numerical procedure is discussed. In section 4,5 validation of numerical simulation and discussion on obtained results are presented respectively .

Problem Statement and Boundary Conditions: Consider a two-dimensional cross sectional view of horizontal annuli with L/D = 0.8 (Fig.1a). The annulus between the two cylinders is filled with the Cu-water nanofluid as phase change material. It was assumed that the flow is laminar and the base fluid and the nanoparticles are in thermal equilibrium and no slip occurs between them.

Thermo-physical properties of the Nanofluid are assumed to be constant except for the density variation, which is approximated by the Boussinesq model.

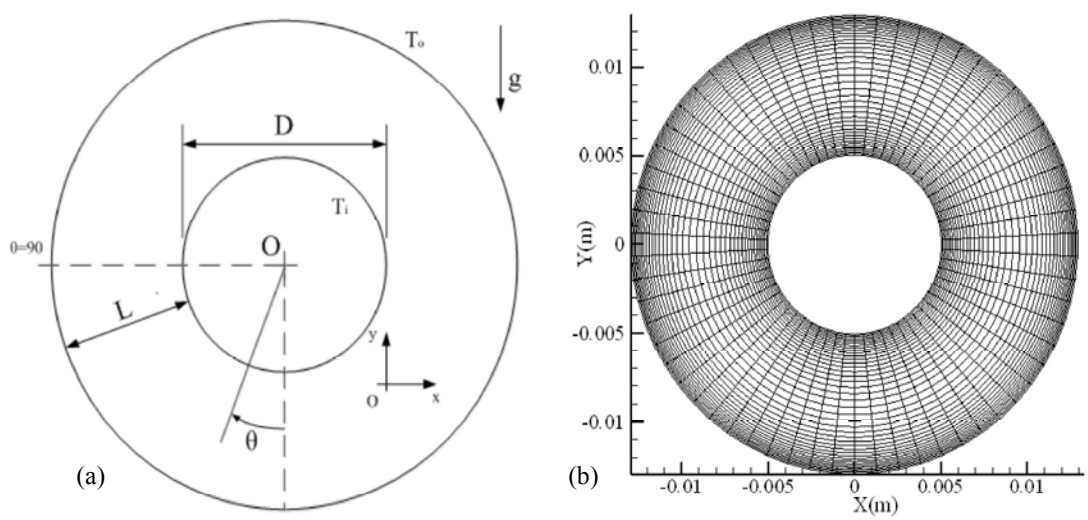


Fig. 1: Sketh and mesh of the problem geometry.

Table 1: Thermo-physical properties

	Cu (Nano particle)	Water (Base fluid)
ρ [kg/m3]	8954	997.1
μ [Pa s]	___	8.9e-4
cp [J/kg K]	383	4179
k [W/m K]	400	0.6
L [J/kg]	__	3.35e5
Pr	___	6.2

The thermo-physical properties of the base fluid and nanoparticle which were used for simulation are given in Table 1. The outer cylinder surface is maintained at solidification temperature ($T_o = T_l$) which is higher than the inner cylinder temperature (T_i).We assume the initial temperature $T_{initial}$ =20 and $\Delta T = Tout\text{-}Tin$

Governing Equation and Computational Procedure: In order to simulate phase change of NEPCM in the horizontal concentric annulus, enthalpy-porosity method [12,13] was used. It is worth to note here that Bertrand *et al.* [14] present the results of a comparison exercise in which various numerical approaches were applied to a phase-change problem that included coupled natural convection and melting. The results indicate that enthalpy methods are to be used in most phase-change problems where a solid-liquid interfacial region is present between the phases.

Considering the Nanofluid as a continuous media with thermal equilibrium between the base fluid and the solid Nanoparticles, the governing equations used here for the modeling of specified nanofluid as PCM are [13,15,16]:

Continuity:

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

Momentum Equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho_{nf}}\left(-\frac{\partial P}{\partial x}+\mu_{nf}\nabla^2 u\right)+S_x \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=\frac{1}{\rho_{nf}}\left(-\frac{\partial P}{\partial x}+\mu_{nf}\nabla^2 v+(\rho\beta)_{nf}\,g\left(T-T_{ref}\right)\right)+S_y \tag{3}$$

Energy Equation:

$$\frac{\partial(C_{p,nf}T)}{\partial t}+u\frac{\partial(C_{p,nf}T)}{\partial x}+v\frac{\partial(C_{p,nf}T)}{\partial y}= \frac{\partial}{\partial x}\left[\frac{\left(k_{nf0}+k_d\right)}{\left(\rho C_p\right)_{nf}}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\left(k_{nf0}+k_d\right)}{\left(\rho C_p\right)_{nf}}\frac{\partial T}{\partial y}\right]-S_h \tag{4}$$

The Density of the Nanofluid Is Given By:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_S \tag{5}$$

Whereas the heat capacitance of the Nanofluid and part of the Boussinesq term are [7]:

$$(\rho c_p)_{nf}=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_s \tag{6}$$

$$(\rho\beta)_{nf}=(1-\phi)(\rho\beta)_f+\phi(\rho\beta)_s \tag{7}$$

with ϕ being the volume fraction of the solid particles and subscripts *f*, *nf* and *s* stand for base fluid, Nanofluid and solid Nanoparticles, respectively. The viscosity of the Nanofluid containing a dilute suspension of small rigid spherical particles is given by [16]:

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \tag{8}$$

Whereas the thermal conductivity of the stagnant (subscript 0) Nanofluid and the effective thermal conductivity of the Nanofluid are [4]:

$$\frac{k_{nf0}}{k_f}=\frac{k_s+2k_f-2\phi(k_f-k_s)}{k_s+2k_f+\phi(k_f-k_s)},\quad k_{eff}=k_{nf0}+k_d \tag{9}$$

and the thermal conductivity enhancement term due to thermal dispersion is given by:

$$k_d=q\left(\rho C_p\right)_{nf}\sqrt{u^2+v^2}\phi d_p \tag{10}$$

The empirically-determined constant q is evaluated following the work of Wakao and Kaguei [17].

In Eq. (2), (3) and (4), *S* is the source term and *h* is the specific enthalpy. The latter is defined as a sum of the sensible enthalpy $h=h_{ref}+\int_{T_{ref}}^{T}C_p dT$ and the enthalpy change due to the phase-change *fL*, where *L* is latent heat energy and *f* is the liquid fraction during the phase change which occurs over a range of temperatures $T_{solid}, < T < T_{liquid}$ defined by the following relations:

$$f=\begin{cases}0 & if \quad T<T_{solid}\\ \dfrac{T-T_{solid}}{T_{liquid}-T_{solid}} & if\ T_{solid}<T<T_{liquid}\\ 1 & if \quad T>T_{liquid}\end{cases} \tag{11}$$

Table 2: Grid independency test at $\phi = 0, \Delta T = 10$

Grid size	Liquid fraction t=1600 s
124.80	26.35
62.40	26.32
31.20	25.1

The source S_h of the energy equation is given by:

$$S_h = -\frac{\partial[\rho L(f)]}{\partial t} \tag{12}$$

The source term S in the momentum equation, is given by

$$S_x = \frac{C(1-f)^2}{f^3+\varepsilon}u, \quad S_y = \frac{C(1-f)^2}{f^3+\varepsilon}v \tag{13}$$

where $A(f) = \frac{C(1-f)^2}{f^3+\varepsilon}$ which causes the gradually reduction of the velocities from a finite value in the liquid, to zero in the full solid, over the computational cells that are changing phase. This function is where $\varepsilon = 0.001$ is a small computational constant used to avoid division by zero and C is a constant reflecting the morphology of the solidification front. This constant is a large number, usually 10^4 _ 10^7 . In the current study C is set to $1.6*10^6$.

A code has been developed to solve the governing equation via the finite volume method using SIMPLE algorithm on collocated body-fitted grids. The convection fluxes discretized by the first order upwind scheme, diffusion term discretized by the central difference approximation. the grid resolution study done on coarse to fine grids is shown in table 2. Finally, the 62*40 grid was applied (Fig.1b).

Validation of the Model: In order to validate the implementation of mathematical modeling melting and solidification in our finite volume CFD code, numerical simulation of melting of gallium by Brent *et al.* [18] which are very analogous with experimental results of C.Gau and R.Viskanta [19], is considered and the comparison of the phase front propagation is demonstrated in Fig.2. A reasonably good agreement is obtained. The slight difference is due to higher accuracy of the discrimination schemes used by brent *et al.*

Also comparison of the obtained results of solidification of the NEPCM is in good agreement with numerical results of the work of J.M.Khodadadi and S.F.Hosseinzadeh [7] Fig.3.

And for the last validation, natural convection of air in the considered geometry is compared with the experimental work of Kuhen and Goldstein [20] Fig.4.

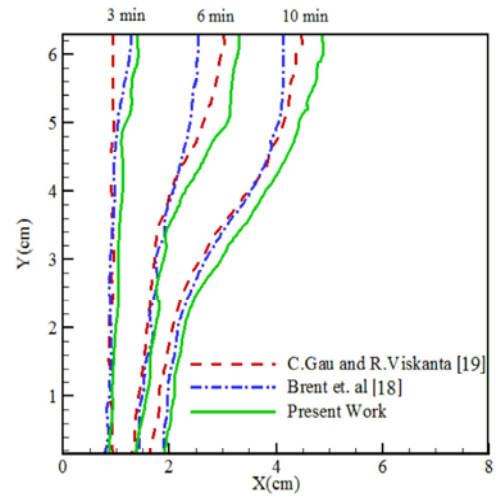


Fig. 2: Progress of melting front with time: Comparison among predictions of Brent *et al.* [18],C.Gau[19] and present work

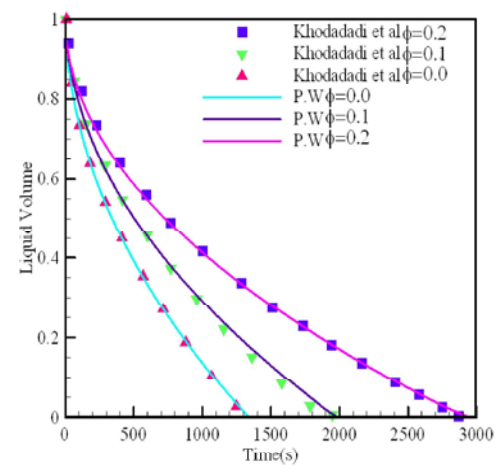


Fig. 3: Comparision of the results of the present work (solidline) and numerical results of J.M.Khodadadi and S.F.Hosseinzadeh [7].(Gr = 10^5)

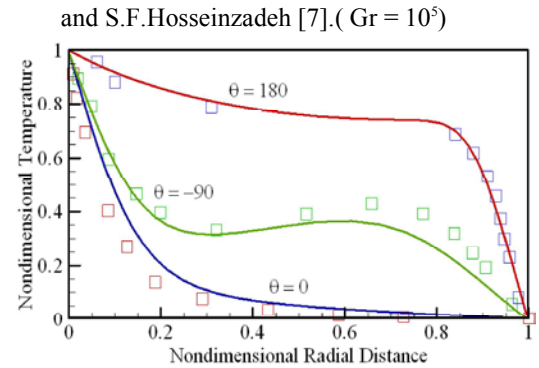


Fig. 4: Code validation of natural convection in concenteric annulus :Comparision of the results of the present work (solidline) and kuhen and goldstein [20] experimental results (square symbol) (Ra= 4.7×10^4,Pr=0.706,and L/D=0.8)

RESULTS AND DISCUSSIONS

The heat transfer phenomena here consist of both the convective and conductive mode of energy transfer. To explain the physical phenomena, Colorized contours of the liquid volume fraction of the nanofluid are shown at various time in Fig 5. It should be mentioned that the color red is used to identify the liquid phase, whereas color blue is indicative of the frozen solid phase. Phase front progress for Gr=10^6 and nanoparticle volume fraction of 0.05 along with temperature contour is shown in fig 5. At the beginning of the solidification process, convection is still coexisting with conduction in liquid phase and thus the difference in phase velocities is obvious. But after 100s convection would be negligible and the heat transfer mechanism is mainly due to conduction and isotherms are approximately concentric.

Fig. 6 shows the effects of Nano particle addition on phase front. It is clear from Fig. 6. That solidification phase front progress is faster in comparison with low dispersion of Nano particle. This is because of the increase in thermal conductivity of Nanofluid and then increasing heat transfer rate.

Fig. 7 shows the temperature and velocity distribution variation and the effect of nano particle volume fraction on radial plate with angle θ = 90 for different solidification time. the temperature profiles along the plate in three different solid particle volume fractions are shown. At the beginning of the process, There is a significant temperature drop at inner and outer cylender surfaces which in result led to two clockwise vortex. Meanwile solidification had been started from the inner cylinder toward the outer one and in few seconds temperaturate variation in anuulus is vanished and

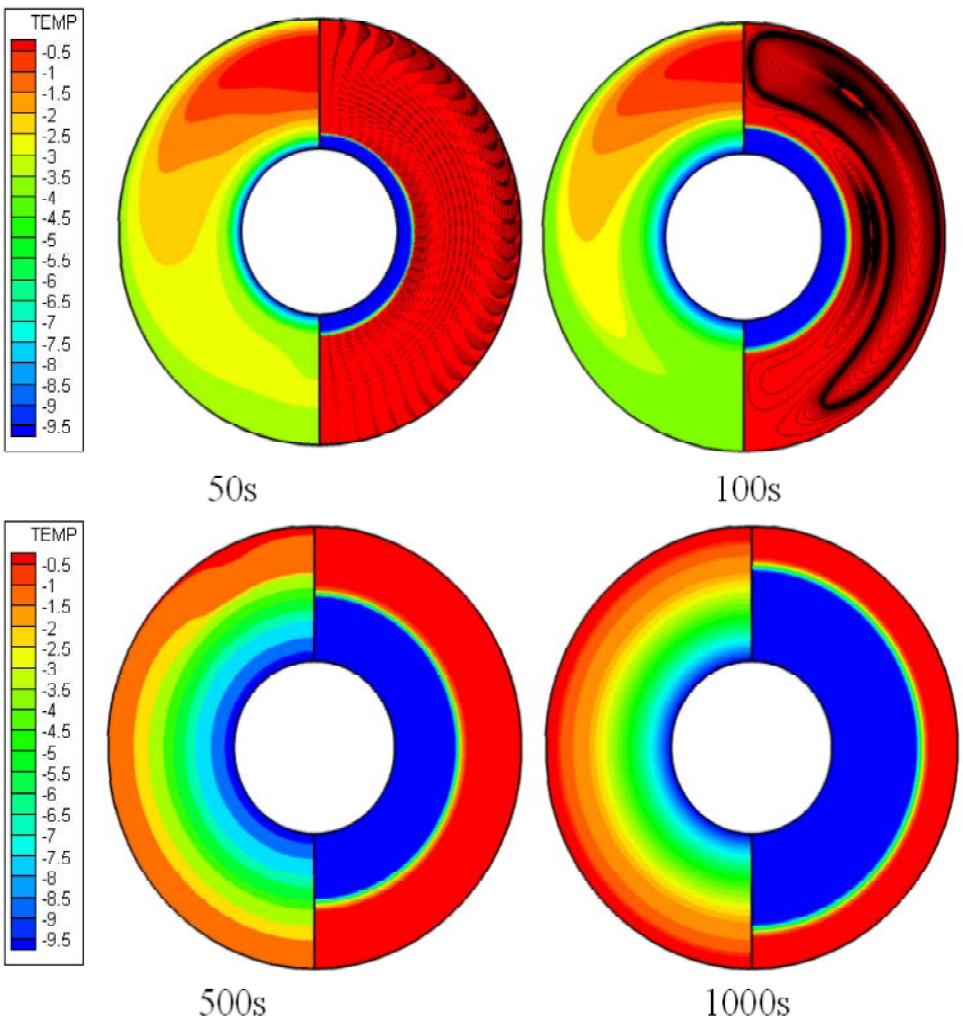


Fig. 5: Phase front(Right) and isoterms(left) of the nanofluid at various time at constant ΔT = 10

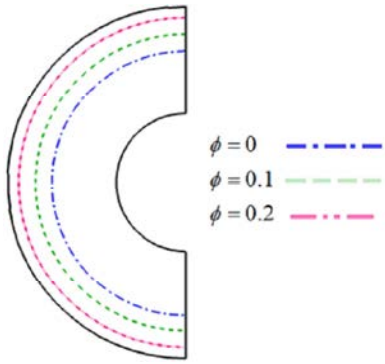
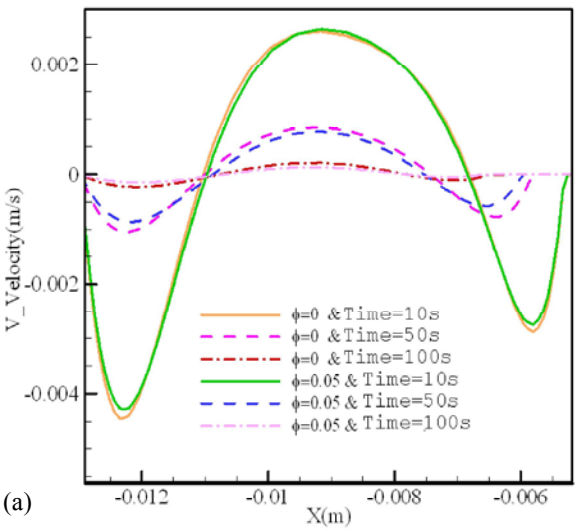
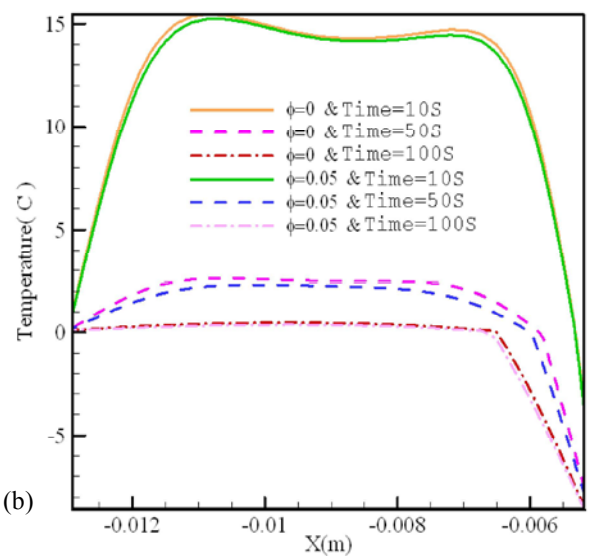


Fig. 6: Phase front propagation at 1000 sec for different nanoparticle volume fraction



(a)



(b)

Fig. 7: Temperture and velocity history at radial plate $\theta = 90$

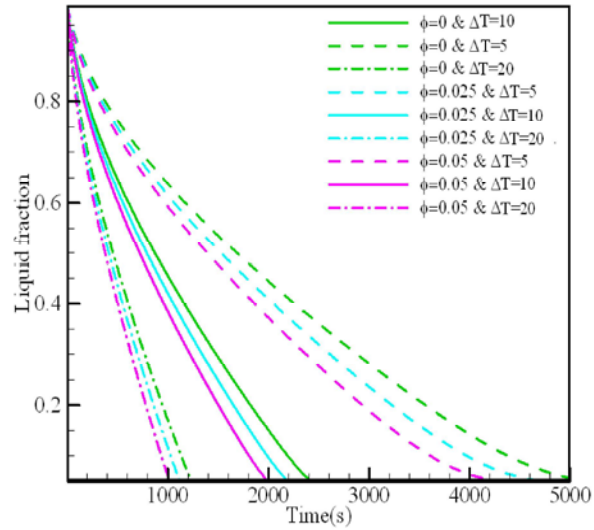


Fig. 8: Instantanous liqiuid volume fraction within annulus

velocity convergers to zero and therefore natural convection effects disappear and heat conduction is the dominant mode of heat transfer in both solid and liquid. As it is obvious from fig. 5, increasing in nanoparticle volume fraction is twofold. First it results in increasing of the nanofluid viscosity and decrease in velocity and secod increasing in thermal conductivity leads to increase in heat transfer rate and consequently uniforming of temperature distribution in liquid phase occurs faster.

Fig. 8 shows the liquid fraction versus solidification time for different Nano particle volume fraction and different temperature differences. It can be conclude from Fig. 6 that increasing both nano particle volume fraction and temperature difference causes the reduction of total solidification time. This behavior shows the efficiency of the nano-particle usage for different temperature ranges in various applications.

CONCLUSION

The effects of nano particle dispersion in a concenteric anului is investigitated for different temperature ranges.the present study illustrate that the suspended nanoparticles increase the heat transfer rate and substantially decrease the solidification time. In the end, it is shown that using proper suspension of nanoparticles within conventional phase change materials has the potential of improving the treditional energy storage system.

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We would like to appreciate Dr. S.F.Hosseinizadeh who made it possible for us to prepare this Article and it is unfortunate to say that the Society of nanotechnology and aerospace lost him just 10 days before we submit this paper. May his soul faithful by God's mercy. Rest in peace

REFERENCES

1. Zalba, B., J. Marin, L.F. Cabeza, H. Mehling, 2003. Review on thermal energy storage with phase change materials, heat transfer and analysis and applications, Appl. Therm. Eng., 23: 251-283.
2. Kenisarin, M. and K. Mahkamov, 2007. Solar energy storage using phase change materials, Renewable Sustainable Energy. Rev., 11: 1913-1965.
3. Jegadheeswaran, S. and S.D. Pohekar, 2009. Performance enhancement in latent heat thermal storage system: A review, Renewable Sustainable Energy. Rev., 13: 2225-2244.
4. Godson, L., B. Raja, D.M. Lal, S. Wongwises, 2010. Enhancement of heat transfer using nanofluids-An overview, Renewable Sustainable Energy Rev., 14: 629-641.
5. Xuan, Y. and Q. Li, 2003. Investigation on Convective Heat Transfer and Flow Features of Nanofluids, J. Heat. Transfer, 125: 151-155.
6. Keshavarz moraveji, M., H. Hezave, R. Davarnejad, 2010. A New Model for the Thermal Conductivity Prediction of Al2o3 and Cuo Nanofluid in Water, Word Applied Sci., 9(10): 1095-1099.
7. Khodadadi, J. and S.F. Hosseinizadeh, 2007. Nano particle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage, Int. J. Comm. Heat. Mass. Transfer, 34: 534-543.
8. Ranjbar, A.A., S. Kashani, S.F. Hosseinizadeh ands M. Ghanbarpour, Numerical Heat Transfer Studies of a Latent Heat Storage System Containing Nano-Enhanced Phase Change Material, J. Thermal. Sci., 15(2011): 169-181.
9. Khodadadi, J.M. and L. Fan, 2009. Expedited Freezing of Nanoparticle-Enhanced Phase Change Materials (NEPCM) Exhibited Through a Simple 1-D Stefan Problem Formulation, ASME Conference Proceedings, 1: 345-351.
10. S. Wu, D. Zhu, X. Zhang and J. Huang, 2010. Preparation and Melting/Freezing Characteristics of Cu/Paraffin Nanofluid as Phase-Change Material (PCM), Energy Fuels, 24: 1894-1898.
11. Wu, S., D. Zhu, X. Li, H. Li and J. Lei, Thermal energy storage behavior of Al2O3-H2O nanofluids, Thermochim. Acta., 483: 73-77.
12. Voller, V.R. and C. Prakash, 1987. A fixed-grid nume rical modeling methodology for convection-diffusion mushy region phase-change problems, Int. J. Heat Mass Transfer, 30(8): 1709-1719.
13. Dutta, R., A. Atta and T.K. Dutta, 2008. Experimental and Numerical Study of Heat Transfer in Horizontal Concentric Annulus Containing Phase Change Material Can. J. Chem. Eng., 86:700-710.
14. Olivier Bertrand, Bruno Binet, Herve Combeau, Stephane Couturier, Yves Delannoy, Dominique Gobin, Marcel Lacroix, Patrick Le Quere, Marc Medale, Jure Mencinger, Hamou Sadat and Gisele Vieira, 1999. Melting driven by natural convection: A comparison exercise, Int. J. Therm. Sci., 38: 5-26.
15. Khanafer, K., K. Vafai and M. Lightstone, 2003. Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids, Int. J. Heat. Mass. Transfer, 46(19): 3639-3653.
16. Eiyad Abu-Nada, 2009. Effects of variable viscosity and thermal conductivity of Al2O3-water nanofluid on heat transfer enhancement in natural convection, Int. J. Heat and Fluid Flow, 30: 679-690.
17. Wakao, N., S. Kaguei, Heat and Mass Transfer in Packed Beds, 1982. Gordon and Breach Science Publishers, New York, pp: 175-205.
18. Brent, A.D., V.R. Voller and K.J. Reid, 1988. Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, Numer. Heat Transf., 13(3): 297-318.
19. Gau, C. and R. Viskanta, 1986. Melting and solidification of a pure metal on a vertical wall, J. Heat Transfer, 108(1): 174-181.
20. Kuhen, T.H. and R.J. Goldstein, 1976. An experimental and theoretical study of natural convection in the annulus between horizontal concentric cylinders, J. Fluid Mechanics, 74: 695-719.