Journal of mathematics and computer Science 8 (2014) 21 - 27

Contents list available at JMCS

Journal of Mathematics and Computer Science

Journal Homepage: www.tjmcs.com

Solidification of Nano-Enhanced Phase Change Material (NEPCM) in an Enclosure

M. Hosseini[1], M. Shirvani [2], A. Azarmanesh[3]

[1]Islamic Azad University, Department of Mechanical Engineering, Qaemshahr Branch, Iran
[2]Islamic Azad University, Department of computer Engineering, Babol Branch, Iran
[3]Babol University Pnu, Department of Indutsrial Engineering P. O. Box: 484, Babol, Iran.

Article history:
Received February 2013
Accepted May 2013
Available online June 2013

Abstract

The effects of nanoparticle dispersion ($\phi = 0, 0.025, 0.05$) on solidification of different type of mixture of nanofluids namely, Cu-water, TiO_2-Water and Al_2O_3-Water nanofluid inside a vertical enclosure are investigated numerically for different Grashof number ($Gr = 10^4, 10^5, 10^6$). An enthalpy porosity technique is used to trace the solid and liquid interface. Comparisons with previously published works show the accuracy of the obtained results. A maximum of 16% decrease in solidification time for $Gr=10^6$ in comparison with $Gr=10^5$ was found with the Cu nanoparticles and 0.2% volume fraction. It was observed that dispersion of nanoparticles can be used to control the solidification time based on enhancing conduction heat transfer mechanism of solidification.

Keywords: Nanoparticle; Nanofluid; Solidification; Phase change material.

1. Introduction

Mixed convection in ventilated cavities has received a sustained attention, due to the interest of the phenomenon in many technological processes and engineering systems, such as the design of solar collectors, thermal design of buildings, air conditioning solar energy storage, heat exchangers, lubrication technologies and drying technologies. In ventilated enclosures, the interaction between the external forced stream and the buoyancy driven flow induced by buoyancy forces could lead to complex flow structures. Various researchers have carried out investigations into the effect of mixed convective flows in rectangular enclosures. [1-3]. Heat transfer fluids such as water play important roles in many industrial applications, but low thermal conductivity is a primary limitation in the development of energy-efficient heat transfer fluids. Therefore a new class of heat transfer fluids known as nanofluids can be designed by suspending metallic nanoparticles in conventional heat transfer fluids. Use of metallic nanoparticles with high thermal conductivity will increase the effective thermal conductivity of these types of fluid remarkably. A numerical study of natural convection of copper–water nanofluid in a two dimensional enclosure was conducted by Khanafer *et al.* [4]. Other researches have been conducted that simulate the convection heat transfer using nanofluid in the other geometrical configurations [5-12].

The aim of the present study consists in studying numerically a mixed convection flow and heat transfer of Cu-Water nanofluid in a ventilated cavity with constant heat flux on one of its vertical walls. In this analysis, the forced flow enters the cavity through an opening located in the middle of the heated vertical wall and leaves it from an opening located at the end of top opposite adiabatic wall. Indeed this geometry has the potential application in a cooling of electronic device. In the end, the consequence of varying the Reynolds number, Richardson number and the nanoparticle concentration on the hydrodynamic and thermal characteristics have been investigated and discussed.

2. Problem formulation and Governing Equations

The two-dimensional configuration under study with the system of coordinates is sketched in Fig. 1. The cavity is filled with a suspension of copper nanoparticles in water. The vertical left wall is heated by a uniform heat flux while the remaining are considered perfectly insulated. The cavity is subjected to an external jet of nanofluid entering in to cavity from the opening located in left vertical wall and leaving from the opening of the top horizontal one.

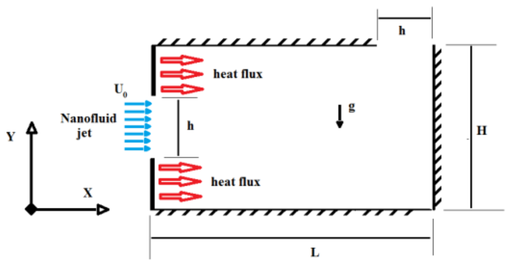


Fig. 1. Schematic of the studied configuration.

Property	*Cu Nanoparticle*	*Base fluid(water)*
$\rho\left[kg/m^3\right]$	8954	997.1
$\mu[Pa.s]$	---	8.9e-4
$c_p\left[J/kg\ K\right]$	383	4179
$k\left[W/m\ K\right]$	400	0.6
Pr	---	6.2
$d_p[m]$	10^{-9}	---

Table 1- Thermophysical properties of the Cu nanoparticles and base fluid (water)

The shape and size of solid particles are assumed to be uniform and the diameter of them to be equal to 100 nm. It is assumed that both the fluid phase and nanoparticles are in thermal equilibrium and there is no slip between them. Except for the density the thermo physical properties of nanoparticles and fluid are taken to be constant. The thermo physical properties of the base fluid (Water) and nanoparticles (Cu) are shown in Table 1. It is further assumed that the Boussinesq approximation is valid for buoyancy force. The governing equations for the steady, two-dimensional laminar and incompressible mixed convection flow with negligible viscous dissipation are expressed as below:

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

$$\rho_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\rho_{nf}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+(\rho\beta)_{nf}\,g\left(T-T_c\right) \tag{3}$$

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

The effective density ρ_{nf}, the effective dynamic viscosity μ_{nf}, the heat capacitance $(\rho Cp)_{nf}$ and the thermal conductivity $k_{nf}$of the nanofluid are given as[13]:

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

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

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

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

The effective thermal conductivity of nanofluid can be defined as the sum of thermal conductivity of the stagnant (subscript 0) Nanofluid and the thermal conductivity enhancement term due to thermal dispersion.

$$k_{nf} = k_{nf,0} + k_d \tag{9}$$

The thermal conductivity of the stagnant Nanofluid for spherical nanoparticles, according to Maxwell [14], is:

$$\frac{k_{nf0}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)} \tag{10}$$

In our modeling, the nanofluid is treated as a single phase fluid but the additional heat transfer enhancement obtained with nanofluids is considered by modeling the dispersion phenomenon. It was noted that thermal dispersion occurs in nanofluid flow due to the random motion of nanoparticles and considering the fact that this random motion creates small perturbations in velocity and temperature. The thermal conductivity enhancement term due to thermal dispersion is given by:

$$k_d = C\left(\rho C_p\right)_{nf} \sqrt{u^2 + v^2}\,\varphi d_p \tag{11}$$

where the empirically-determined constant C is evaluated following the work of Wakao and Kaguei [15]. Equations (1)–(4) can be converted to non-dimensional forms, using the following non-dimensional parameters:

$$X = \frac{x}{H}, Y = \frac{y}{H}, U = \frac{u}{U_0}, V = \frac{v}{U_0}, P = \frac{p}{\rho_f U_0^2}, \theta = \frac{T - T_c}{q'H / k_f}$$
$$, \Pr = \frac{\nu_f}{\alpha_f}, Gr = \frac{g\beta_f q' H^4}{k_f \nu_f^2}, \rho^* = \frac{\rho_{nf}}{\rho_f}, \mu^* = \frac{\mu_{nf}}{\mu_f}, \mathrm{Re} = \frac{U_0 H}{\nu_f} \tag{12}$$

The local and average Nusselt number for the heated vertical wall of the enclosure is calculated as

$$Nu = \frac{K_{eff}}{K_f}\frac{1}{\theta_s(y)} \tag{18}$$

$$Nu_{ave} = \frac{1}{H-h}\left(\int_0^{0.5(H-h)} Nu\,dy + \int_{0.5(H+h)}^{H} Nu\,dy\right) \tag{19}$$

3. Numerical Procedure and Code Validation

The governing equations together with the boundary conditions of the present problem were iteratively solved by the finite-volume-method numerical procedure based on the SIMPLE algorithm of Patankar [16] on a staggered grid arrangement. The QUICK scheme is used for the convective terms and the central difference scheme is used for the diffusive terms. The resulting system of algebraic equations is solved iteratively by using tri-diagonal matrix algorithm (TDMA). The iteration is carried out until the normalized residual of the mass, momentum and temperature equation become less than 10^{-7}. In order to determine the proper grid size for this study, a grid independence test is conducted for $Ri = 1$ and $Ri = 100$. A non-uniform grid mesh which is showed in Fig. 2 is chosen to increase the accuracy of the results. Table 2 demonstrates the influence of number of grid points for pure fluid for $Ri = 10$ as a test case of fluid confined within the present configuration. It is found that the 125×150 grid is fine enough to ensure a grid independent solution. The present numerical code was validated against the results of Khanafer*et al.* [4] for natural convection of Cu–water nanofluid in an enclosure with as shown in Figs. 2 and 3. This comparison revealed good agreements between results. Moreover another test for validation of this numerical method has been performed and demonstrated for the lid-driven square cavity filled by pure fluid. Fig. 4 compares the results of the present study for special cases with those of Shahi*et al.* [8]. It can be seen from the comparison that both solutions are in a good agreement with each other.

4. Results and discussion

Numerical investigation of mixed convection heat transfer of Cu nanofluid is considered in a two-dimensional ventilated rectangular enclosure. Constant heat flux is considered at the vertical walls of inlet portion. Results are presented and discussed for a range of Ri=1, 10, 100, Re= 10, 500, 1000 and Nanoparticle volume fraction $\phi = 0\%, 10\%, 20\%$. While the relative height of the openings $B = h / H$ is marinated constant at 1/4 the aspect ratio of the enclosure, $A = L / H$ is constant at 2. The Streamlines and temperature contours for various Richardson numbers for both pure and nanofluid are shown in Fig. 5.The Variation of the Maximum Temperature at the heat source surface with Reynolds number for different volume fractions is presented in Fig. 6. In Fig. 7, the effect of Reynolds number and volume fraction on the average Nusselt number of the heat source wall is plotted graphically.

Number of grid	Nuave
50×60	8.976
60×72	8.891
86×103	8.625
103×124	8.382
125×150	8.279
150×179	8.268

Table 2- Grid independency examination

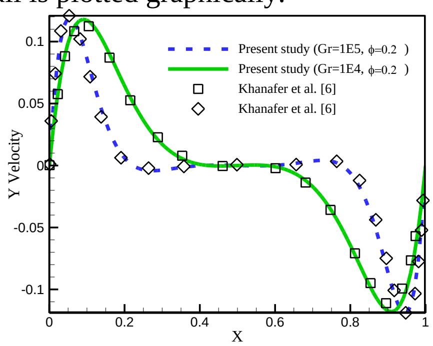


Fig. 2- Comparison of the temperature profiles of nanofluid for Gr=10^4-10^5 and $\phi = 0.2$ obtained by present study and the work of Khanafer et al.[6]

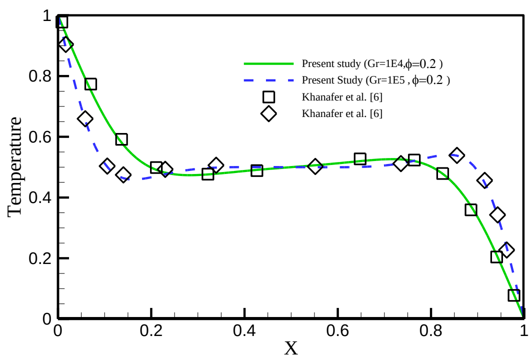


Fig. 3- Comparison of the Y-velocity of nanofluid for Gr=104 105 and $\phi = 0.2$ obtained by present study and the work of Khanafer et al.[4]

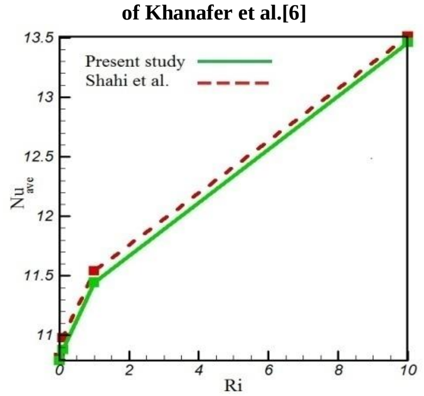
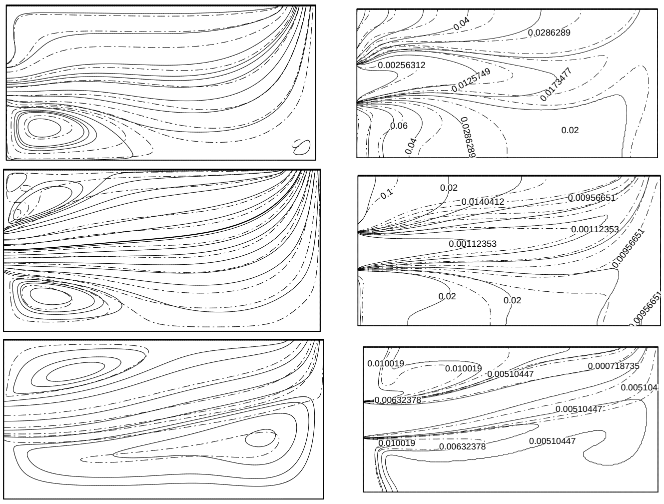


Fig. 4- Comparison of the Average Nusselt number obtained by present study and the work of Shahi*et al.*[8]

Ri=100

Ri=10

Ri=1



Streamline Isotherms

Fig. 5- Streamline and isotherm contours for various Ri values at ϕ =0% (Dashed-Dot Line) and ϕ =10% (Solid Line) for nanofluid

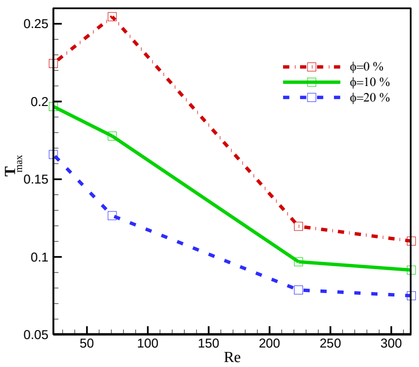


Fig. 6- Variation of the Maximum Temperature at the heat source surface with Reynolds number for different volume fractions.

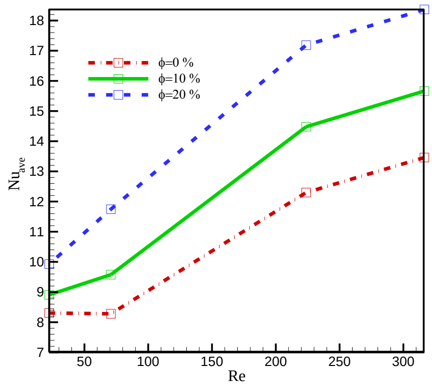


Fig. 7- Variation of the average Nusselt number at the heat source surface with Reynolds number for different volume fractions.

6. Conclusion

The study of mixed convective flow and heat transfer of a nanofluid made up of water and Cu in a ventilated cavity, heated from its vertical left wall with a constant heat flux and thermally insulated from its remaining boundaries, was formulated and solved numerically using the finite-volume method. By comparison of the resulted obtained in this study with previous literatures, a good agreement is found. For different parameters of Richardson number, Reynolds number, Volume fraction of nanoparticles are considered to predict the heat transfer and flow performance. The addition of nanoparticles showed an improvement in the heat transfer rate of the enclosure.

References

[1] J. Khodadadi and S. F. Hosseinizadeh. Nano particle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage, Int. J. Comm Heat Mass Transfer, (2007) 34:534-543

[2] B. Zalba, J. Marin, L.F. Cabeza , H. Mehling, Review on thermal energy storage with phase change materials, heat transfer and analysis and applications, Appl. Therm. Eng. 23 (2003) 251-283.

[3] A. Robert Huggins, Energy Storage, Springer New York Heidelberg Dordrecht London, (2010)

[4] H. Mehling, L.F. Cabeza, Heat and cold storage with PCM: An up to date introduction into basics and applications, Springer-Verlag Berlin Heidelberg,(2008).

[5] A. Sharma, V. Tyagi, C. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009; 13(2):318–45.

[6] S. Jegadheeswaran, S.D. Pohekar. Performance enhancement in latent heat thermal storage system: A review, Renewable Sustainable Energy Rev. 13(2009)2225-2244
[7] M. Kenisarin and K. Mahkamov. Solar energy storage using phase change materials, Renewable Sustainable Energy Rev. 11 (2007)1913–1965.
[8] U.S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, in: Developments and Application of Non-Newtonian Flows, ASME, FED-Vol. 231/MD-Vol. 66, 99–105, (1995)
[9] L. Godson, B. Raja, D.M. Lal, S. Wongwises. Enhancement of heat transfer using nanofluids an overview, Renewable Sustainable Energy Rev. 14 (2010) 629–641.
[10] A.A. Ranjbar, S. Kashani, S.F. Hosseinizadeh, M. Ghanbarpour, Numerical Heat Transfer Studies of a Latent Heat Storage System Containing Nano-Enhanced Phase Change Material, J.Thermal science (in press).
[11] J.M. Khodadadi, L. Fan, Expedited Freezing of Nanoparticle-Enhanced Phase Change Materials (NEPCM) Exhibited Through a Simple 1-D Stefan Problem Formulation, ASME Conference Proceedings 1(2009) 345-351.
[12] S. Wu, D. Zhu, X. Li, H. Li, J. Lei. Thermal energy storage behavior of Al2O3–H2O nanofluids, Thermochim. Acta 483 (2009) 73–77
[13] J.C. Maxwell, A Treatise on Electricity and Magnetism.Clarendon Press, Oxford, UK, second edition (1881).
[14] K. Khanafer, K. Vafai, M. Lightstone. Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids, Int. J.Heat Mass Transfer 46 (19) (2003) 3639–3653.
[15] Xiang-Qi Wang, Arun S. Mujumdar. A Review on Nanofluids - Part I: Theoretical and Numerical Investigations, Brazilian Journal of Chemical Engineering 25 (04) (2008) 613 – 630.
[16] Y. Xuan and W. Roetzel, Conceptions for Heat Transfer Correlation of Nanofluids, Int. J. Heat Mass Tran, 43(19) (2000) 3701-3707.
[17] J. Buongiorno, Convective Transport in Nanofluids, J. Heat Transfer, 128(3) (2006) 240-250.
[18] R.B. Mansour, N. Galanis and C.T. Nguyen, Effect of Uncertainties in Physical Properties on Forced Convection Heat Transfer with Nanofluids, Appl. Therm. Eng., 27(1) (2007) 240-249.
[19] S.Z. Heris, M.N. Esfahany and G. Etemad, Numerical Investigation of Nanofluid Laminar Convective Heat Transfer through a Circular Tube, Numer. Heat Tr. A-Appl., 52(11) (2007) 1043-1058.

[20] V. Bianco, F. Chiacchio, O. Manca and S. Nardini, Numerical Investigation of Nanofluids Forced Convection in Circular Tubes, Appl. Therm. Eng., 29(17-18) (2009) 3632-3642.
[21] X. Wang and A.A. Mujumdar, Review on Nanofluids - Part I: Theoretical and Numerical Investigations, Braz. J. Chem. Eng., 25(4) (2008) 613-630.
[22] H. Masuda, A. Ebata, K. Teramae, N. Hishinuma. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles,NetsuBussei 7 (4) (1993) 227–233.
[23] S. Lee, S. U.-S. Choi, S. Li, and J. A. Eastman. Measuring Thermal Conductivity ofFluids Containing Oxide Nanoparticles, Transactions of the ASME, Journal of Heat Transfer 121 (1999) 280-289.
[24] Argonne National Laboratory, Energy Systems Division Review and Assessment of Nanofluid Technology for Transportation and Other Applications
[25] M. Chopkar, S. Sudarshan, P.K. Das, I. MANNA, Effect of Particle Size on Thermal Conductivity of Nanofluid, The Minerals, Metals & Materials Society and ASM International 39A (2008) 1535-1542.
[26] H. Xie, J. Wang, T. Xi, and F. Ai. Thermal Conductivity Enhancement of Suspensions Containing Nanosized Alumina Particles, Journal of Applied Physics 91: (2002b) 4568-4572.
[27] C. H. Li and G. P. Peterson. Experimental Investigation of Temperature and Volume Fraction Variations on the Effective Thermal Conductivity of Nanoparticle Suspensions (Nanofluids), Journal of Applied Physics 99: 084314 (2006).
[28] S.K. Das, N. Putra, P. Thiesen, W. Roetzel, Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids. Transactions of the ASME, Journal of Heat Transfer 125: 567-574 (2003a).
[29] R.L. Hamilton, O.K. Crosser. Thermal conductivity of heterogeneous two component systems, Ind. Eng. Chem. Fundam. 1 182–191 (1962).
[30] W. Yu, S.U.S. Choi. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model, J. Nanoparticle Res. 5 (2003) 167–171.

[31] F.J. Wasp, J. P. Kenny, R.L. Gandhi, Solid-Liquid Flow Slurry Pipeline Transportation, Trans. Tech. Pub, Berlin. (1977)
[32] V. R. Voller, C. R. Swaminathan. Fixed grid techniques for fase change problems: A Review, International Journal for Numerical Methods in Engineering, Vol. 30,875-898 (1990)
[33] YvanDutil, Daniel R. Rousse, Nizar Ben Salah, Ste´phaneLassue, Laurent Zalewski. A review on phase-change materials: Mathematical modeling and simulations, Renewable and Sustainable Energy Reviews 15 (2011) 112–130.
[34] V.R. Voller, C. Prakash, A fixed-grid numerical modeling methodology for convection diffusion mushy region phase-change problems, Int. J. Heat Mass Transfer 30 (8) (1987) 1709–1719.
[35] J. F. Thompson, Numerical Grid Generation. North-Holland, New York. (1982).
[36] J. F. Thompson, Z. U. Warsi, C. W. Mastin, Numerical Grid Generation, Foundation and Applications. North-Holland, New York. (1985).
[37] H. K. Versteeg, W. Malalasekera, An introduction to computational fluid dynamics the finite volume method. Longman Scientific & Technical, New York. (1995).