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Study of Nanoparticle Fluid Mixtures for Heat Enhancement and Heat Storage in a Cavity

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Abstract

Nanofluids is a class of fluid which contains a solid particle. The base fluid is usually water. The importance of such fluid is its capability of enhanced heat removal. The addition of microencapsulated particle enhances the heat storage. Results revealed an improvement in heat storage. This finding is obvious by examining the Nusselt number for different cases.

Keywords

Nanofluid, heat storage, heat enhancement

1. Introduction

Nanofluid is a class of fluid such as water containing solid particles. These particles have different diameter and made of different materials. The most usually used is Aluminum oxide particles (Al_2O_3). The advantage of adding these particles to water is the increase of conductivity of the mixture. This lead to an improvement in heat removal in some applications such as solar collector. Researchers have conducted different numerical modelling using empirical physical properties which lead to one believe that heat enhancement is around 40%. Of course, this conclusion is misleading because it all depends on the accurate physical properties used in the model [1-18].

With nanofluid being a good fluid for heat removal focus started toward finding a fluid which can be used as a good heat storage. Amongst the candidate for such need is the microencapsulated particles in water known as Microencapsulated Phase Change Material(MEPCM). These microcapsules are good candidate for energy storage and heat transfer applications containing phase change material(PCM). The candidate for PCM could be one of octadecane, or n-pentadecane, or n-eicosane or paraffin wax.

Tseng *et al* [19] demonstrated the preparation of microencapsulated phase change material by means of interfacial polycondensation. Later the core/shell structured microcapsules were also characterized with size distribution analysis, scanning electron microscopy and other different technique. Yamaishi *et al* [20] investigated the hydrodynamic and the heat transfer characteristics of the MEPCM slurry experimentally in a heat transfer experiment. The pressure drop and the convective heat transfer coefficients of the slurry flows in a circular tube with uniform heat flux were measured. The slurry consisted of a microcapsule of octadecane having a diameter ranging from 2-10 µn in diameter in water. The volume fraction of the particles was varied up to 30%. In the presence of high concentration of MEPCM, it was found that the flow changed from turbulent regime to a laminar regime thus a reduction in the pressure drop in the pipe. In addition, it was found that the heat transfer performance has changed and depends on the change in the flow structure. The melting of the capsule increased the local heat transfer coefficient when compared to a non-melting capsule.

This paper will address the importance of using a ternary mixture. The prediction on the performance of the ternary mixtures is discussed. Section 2 presents the finite element formulation. Section 3 presents the studied cases and detailed discussion of the finding for the ternary mixtures and finally Section 4 is the conclusion.

2. Finite Element Model

The thermo fluid problem in this investigation consists of studying the heat removal effect in a square cavity having a length L of 8 cm. The cavity is heated laterally with the top and bottom sides insulated. Thus, the gravity vector is perpendicular to the temperature gradient. The cavity is filled with different mixture consisting of water with aluminum oxide (Al_2O_3) having different concentrations of particle ranging from 0.5%, 1.7% to 3%. The second mixtures consist of MEPCM with water with the microencapsulated phase change material concentration varies by 4%vol, 10%vol and finally 20%vol. In the third case the cavity is filled with a ternary mixture consisting of aluminum oxide nanoparticles, MEPCM nanoparticles and water. In this study, the finite element numerical technique has been used to solve the governing equations for single-phase [21]. Figure 1a depicts the cavity with the boundary conditions and also gravity direction in the simulation model. Figure 1b shows the finite element mesh used in the analysis for both methods. It

Two dimensional governing equations

The fluid is assumed incompressible and single phase. The full Navier-Stokes equation together with the energy equation were solved numerically using the finite element method [21]. The set of non-dimensional term used in our analysis are as follows;

$$U = \frac{u}{U_o}, V = \frac{v}{U_o}, X = \frac{x}{L}, Y = \frac{y}{L}, \theta = \frac{(T-T_c)}{(T_h-T_c)} \text{ and } P = \frac{pL}{\mu U_o} \quad (1)$$

In particular, the momentum equations in non-dimensional form are as follow in different directions,

Momentum equation along X-direction

$$\mathrm{Re}\left(\mathrm{U}\frac{\partial \mathrm{U}}{\partial \mathrm{X}} + \mathrm{V}\frac{\partial \mathrm{U}}{\partial \mathrm{Y}}\right) = -\frac{\partial \mathrm{P}}{\partial \mathrm{X}} + \left(\frac{\partial^2 \mathrm{U}}{\partial \mathrm{X}^2} + \frac{\partial^2 \mathrm{U}}{\partial \mathrm{Y}^2}\right) \quad (2)$$

Where Re is the Reynolds number set equal to $Re = \frac{U_o L}{\nu_m}$. Since in the current analysis, U_o is set equal to $\frac{\alpha_m}{L}$ the Reynolds number becomes the inverse of Prandtl number. Thus $Re = \frac{1}{Pr_m}$.

Momentum equation along Y-direction

$$\mathrm{Re}\left(\mathrm{U}\frac{\partial \mathrm{V}}{\partial \mathrm{X}} + \mathrm{V}\frac{\partial \mathrm{V}}{\partial \mathrm{Y}}\right) = -\frac{\partial \mathrm{P}}{\partial \mathrm{Y}} + \left(\frac{\partial^2 \mathrm{V}}{\partial \mathrm{X}^2} + \frac{\partial^2 \mathrm{V}}{\partial \mathrm{Y}^2}\right) + \mathrm{Ra_m} \,.\, \theta \quad (3)$$

Where Ra_m is the nanofluid Rayleigh number and θ is the non-dimensional temperature.

Continuity equation

The continuity equation for this simulation can be expressed as,

$$\left(\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y}\right) = 0 \quad (4)$$

Energy conservation equation

The energy equation is as follows

$$RePr_m\left(U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y}\right) = \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \quad (5)$$

The expression for Rayleigh number Ra_m and the Prandtl number Pr_m, used in our simulation is

$$Ra_m = \frac{g\rho_m^2 Cp_m \beta_m (T_h - T_c) L^3}{k_m \mu_m} \quad (6)$$

and the Prandtl number is defined as,

$$Pr_m = \frac{Cp_m \mu_m}{k_m} \quad (7)$$

Finally, the average Nusselt number was calculated numerically at the hot wall of the cavity by following the following equation

$$\overline{Nu} = \int_0^1 \frac{\partial \theta}{\partial X} \quad (8)$$

It is important to indicate that the average temperature gradient is then multiplied by the ratio of the conductivity of the base fluid and divided by the conductivity of the mixture in order to obtained the right Nusselt number.

3. Numerical Results

The aim of this current paper is to try to investigate the importance of using a mixture of Al_2O_3 nanoparticles together with MEPCM in water solution for heat storage. Saghir et al [18] have shown that, by using nanofluid via including an aluminum particle in water, one can reach a heat enhancement of 4% compared to regular water.

Effectiveness of ternary mixture in heat storage.

Two cases are treated in this paper. In the first case called Case 1, the ternary mixture is studied at an average temperature of 30ºC thus assuming the MEPCM is not molten. Heat characteristic is investigated in details. Then the same mixture is studied at an average temperature of 37.5ºC thus the MEPCM is in molten condition. When the MEPCM is molten in the ternary mixture one observe experimentally a sudden increase in the heat capacity and the conductivity.

Table 1 shows the Rayleigh number as well as the Prandtl number for different ternary mixtures. As one may notice when MEPCM is in a molten stage one observe an increase in the Prandtl number as well as the Rayleigh number. The problem was solved for the two cases and results revealed that when the MEPCM is in in a molten stage, a sharp increase in the average Nusselt number. This indicate that the heat storage is noticeable when MEPCM is molten. Using MEPCM for heat storage is indeed a good approach for this problem

4. Conclusions

In this present study, a ternary mixture of water, aluminum oxide nanoparticles and MEPCM nano particles was used. This ternary mixture demonstrated the usefulness of using it in heat storage. It has been demonstrated that heat storage capability expressed by the Nusselt number is higher than water and recommended to be applied.

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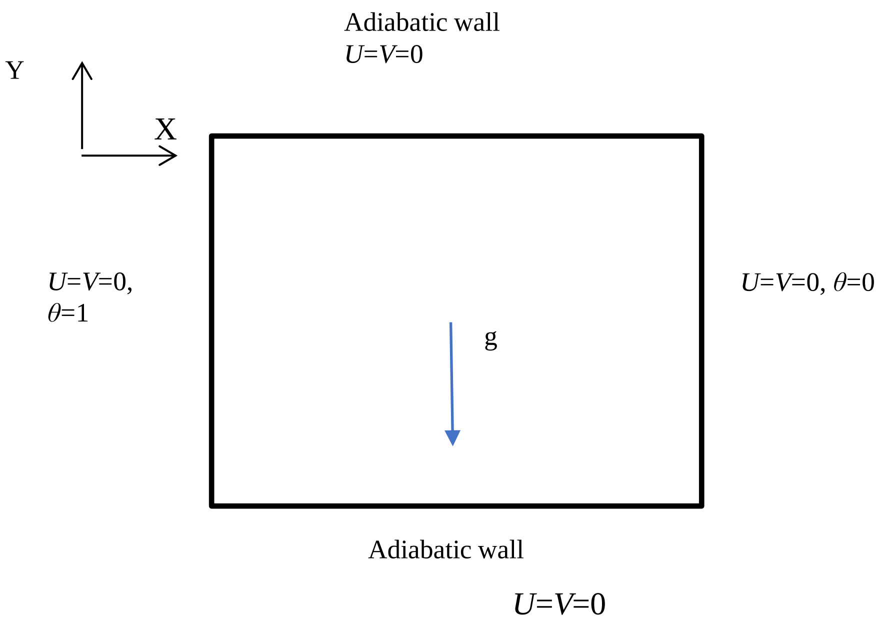
Nomenclature

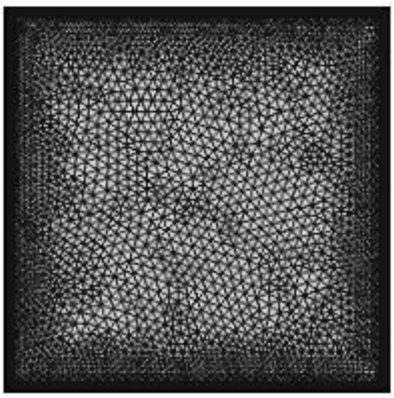
Cp	Specific heat (J/kg. K)	μ	Dynamic viscosity (N/kg. s)
g	Gravitational acceleration (m/s^2)	T	Temperature (K)
k	Thermal conductivity (W/m. K)	U,V	Non-dimensional velocities [1]
L	Characteristic length (m)	X,Y	Non-dimensional coordinates
Nu	Average Nusselt number	U_o	Characteristic Velocity [m/s]
P	Non-dimensional pressure [1]	u,v	Dimensional velocities [m/s]
α	Thermal diffusivity (m^2/s)	v	Kinematic viscosity (m^2/s)
β	Thermal expansion coefficient (1/K)	ρ	Density (kg/m^3)
Subscript			
bf	Base fluid	h	Hot temperature
c	Cold temperature	o	Reference point
m	mixture	p	Particle

Table 1. Physical properties and non-dimensional term values for ternary mixture at different nanoparticles concentration

Mixture T_h-T_c=3ºC	**Case 1** T_{ave}=30ºC			**Case 2** T_{ave}=37.5ºC		
	Pr_m	Ra_m	$\overline{Nu}$	Pr_m	Ra_m	$\overline{Nu}$
0.5%Al_2O_3-4%MEPCM-95.5%Water	12.9639	$1.1633\text{x}10^7$	18.376	21.25	$1.9\text{x}10^7$	19.824
1.77%Al_2O_3-4%MEPCM-94.23%Water	13.8708	$0.89675\text{x}10^7$	17.9423	23.96	$1.66\text{x}10^7$	18.84
3%Al_2O_3-4%MEPCM-93%Water	15.412	$0.64665\text{x}10^7$	16.956	26.87	$1.3\text{x}10^7$	16.92
0.5%Al_2O_3-20%MEPCM-79.5%Water	18.133	$1.209\text{x}10^7$	17.078	71.422	$6.84\text{x}10^7$	31
1.77%Al_2O_3-20%MEPCM-78.23%Water	19.7493	$0.94245\text{x}10^7$	16.791	96.55	$4.76\text{x}10^7$	26.974
3%Al_2O_3-20%MEPCM-77%Water	21.2219	$0.7974\text{x}10^7$	16.63	107.915	$4.13\text{x}10^7$	25.08



(a) Model Geometry and Boundary Conditions



(b) Finite Element Mesh

Fig. 1 Numerical Model Geometry, Boundary Conditions and the Finite Element Mesh