Numerical investigation into heat transfer controllability of a magnetic nanofluid flow under the influence of non-uniform magnetic field

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Abstract

In this paper, results of applying a non-uniform magnetic field on a ferrofluid (kerosene and 4 vol.% Fe3O4) flow in a vertical tube have been reported. The thermal behaviour of the flow is investigated numerically using two phase mixture model and control volume technique. Two positive and negative magnetic field gradients have been examined. Based on the obtained results the Nusselt number can be controlled externally using the magnetic field with different intensity and gradients.

Keywords: Ferrofluid, Mixed Convection, Non-uniform Magnetic Field, Buoyancy Force, Mixture Model.

1. Introduction

Magnetic nanofluid, also called ferrofluid, is a magnetic colloidal suspension consisting of carrier liquid and magnetic nanoparticles with a size range of 5 to 15nm in diameter coated with a surfactant layer. The most often used magnetic material is single domain particles of magnetite, iron or cobalt; and the carrier liquids such as water or kerosene. The advantage of the ferrofluids is that the fluid flow and heat transfer may be controlled by an external magnetic field which makes it applicable in various fields such as electronic packing, mechanical engineering, thermal engineering, aerospace and bioengineering [1& 4].

Many investigations were carried out numerically and experimentally in the field of thermomagnetic convection of the ferrofluids in different geometries in the presence of an external magnetic field [3]. Results of these investigations show that the thermal behaviors of the magnetic fluids inside an enclosure are dominated by both the intensity of the external magnetic field and temperature gradient.

Generally, the numerical simulations have often used a single phase model while ferrofluids are colloidal mixtures. The main aim of this paper is a 3D numerical investigation on the mixed convective heat transfer features of kerosene based ferrofluid flowing upward in a vertical circular tube under the influence of external non-uniform magnetic field using two phase mixture model..

2. Governing equations

Figure 1 shows schematic of the investigated problem. The physical properties of the fluid are assumed constant except for the density in the body force, which varies linearly with the temperature based on the Boussinesq's model. In the present work, dissipation and pressure work are neglected. Considering these assumptions the dimensional conservation equations (i.e., continuity, momentum, energy, and volume fraction respectively) for steady state condition are as follows:

$$\nabla.\left(\rho_m \vec{v}_m\right) = 0. \tag{1}$$

$$\nabla.\left(\rho_m \vec{v}_m \vec{v}_m\right) = -\nabla p + \nabla.\left(\mu_m \nabla \vec{v}_m\right) + \nabla.\left(\alpha_P \rho_P \vec{v}_{dr,p} \vec{v}_{dr,p}\right) - \rho_{m,0}(T - T_0)\beta_m \vec{g} + \mu_0(\vec{M}.\nabla)\vec{H} \tag{2}$$

$$\nabla.\left[\left(\alpha_P \rho_P c_{p,p} \vec{v}_p + (1-\alpha_P)\rho_f c_{p,f} \vec{v}_f\right)T\right] = \nabla.\left(k_m \nabla T\right) \tag{3}$$

$$\nabla.\left(\alpha_P \rho_p \vec{v}_m\right) = -\nabla.\left(\alpha_P \rho_p \vec{v}_{dr,p}\right) \tag{4}$$

Where

$$\vec{v}_m = \frac{\alpha_p \rho_P \vec{v}_p + (1-\alpha_P)\rho_f \vec{v}_f}{\rho_m} \tag{5}$$

$$\vec{v}_{dr,p} = \vec{v}_p - \vec{v}_m \tag{6}$$

are the mass-averaged velocity and drift velocity respectively and α_P is the volume fraction of nanoparticles. The slip velocity is defined as the velocity of a secondary phase (p) with respect to the velocity of the primary phase (f):

$$\vec{v}_{pf} = \vec{v}_p - \vec{v}_f. \tag{7}$$

The drift velocity is related to the slip velocity

$$\vec{v}_{dr,p} = \vec{v}_{pf} - \frac{\alpha_p \rho_P}{\rho_m}\left(\vec{v}_f - \vec{v}_p\right). \tag{8}$$

Considering stokes drag coefficient and forces act on a single magnetic particle, the slip velocity is defined similar to Jafari et al. [2]:

$$\sum \vec{F}_p = 0 \rightarrow \mu_0 m_p L(\xi) \nabla \vec{H} + \left(\rho_p - \rho_f\right) V_p \vec{g} - 3\pi \mu_f d_p \vec{v}_{pf} = 0 \tag{9}$$

$$\vec{v}_{pf} = \frac{\rho_p d_p^2}{18\mu_f} \frac{\rho_p - \rho_f}{\rho_p} \vec{g} + \frac{\mu_0 m_p L(\xi)}{3\pi \mu_f d_p} \nabla \vec{H}. \tag{10}$$

The last term in Eq. (2), is the effect of magnetic field which is the so-called the Kelvin force density, derived from the stress of an electromagnetic field where M is the magnetization and is defined as [4]:

$$M = M_s L(\xi) = \frac{6\alpha_p m_p}{\pi d_p^3}\left(\coth(\xi) - \frac{1}{\xi}\right). \tag{11}$$

The unit cell of the crystal structure of magnetite has a volume of about 730 Å3 and contains 8 molecules Fe3O4 and each of them having a magnetic moment of 4μB [5]. Therefore the particle magnetic moment for the magnetite particles is obtained as:

$$m_p = \frac{4\mu_B \pi d_p^3}{6 \times 91.25 \times 10^{-30}} \tag{12}$$

also ξ is the langevin parameter and is defined as [3]:

$$\xi = \frac{\mu_0 m_p H}{k_B T} \tag{13}$$

The mixture physical properties in the above equations are used as below:

$$\rho_m = \alpha_P \rho_p + (1-\alpha_P)\rho_f \tag{14}$$

$$\mu_m = \left(1 + \frac{5}{2}\alpha_p\right)\mu_f \tag{15}$$

$$k_m = \alpha_P k_p + (1-\alpha_P)k_f \tag{16}$$

$$\beta_m = \left[\frac{1}{1+\frac{(1-\alpha_P)\rho_f}{\alpha_P \rho_P}}\,\frac{\beta_p}{\beta_f} + \frac{1}{1+\frac{\alpha_P \rho_P}{(1-\alpha_P)\rho_f}}\right]\beta_f \tag{17}$$

The set of 3D coupled non-linear differential equations were discretized with the control volume technique. For the convective and diffusive terms a second order upwind method was used while the SIMPLEC procedure was introduced for the velocity–pressure coupling. A structured non-uniform grid has been used to discretize the computational domain.

3. Results and Discussion

The results are presented for kerosene based ferrofluid consisting 4% vol. Fe3O4 particles with 10 nm mean diameter (spherical shape). Physical model is a straight circular tube with the length of 200mm and diameter of 10mm (see Fig. 1).Grashof number for the presented results is 10000. For this value the bulk temperature variation is low enough for reliability of Boussinesq approximation in the range of applied Reynolds numbers. The applied magnetic field is considered to be uniform in radial and circumferential direction and varying linearly in z direction which starts from zero at the z=L/4 and finishes with maximum value at the z=3L/4 for the positive gradient case and vice versa for the negative gradient case (see Fig. 1).

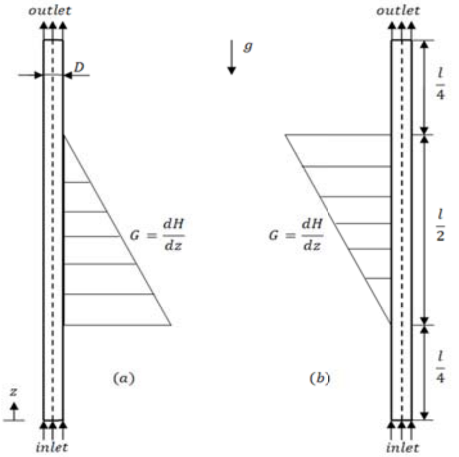

Figure 1: Schematic of physical models with: (a) negative and (b) positive magnetic field gradient.

The external magnetic field effects with different positive and negative gradient values on the local Nusselt number have been presented in Figures 2. For the positive gradient case with starting the magnetic field by zero value at z/D=5, Nusselt number starts to decrease compared to no magnetic field case. Decreasing of the Nusselt number continues insofar as the magnetic field exists. By the sudden elimination of magnetic field at z/D=15, Nusselt number recovers rapidly to the values of no magnetic field case. For the negative magnetic field gradient the behaviour is vice versa. Also these effects increase with increasing the slope of the magnetic field variation.

4. Conclusion

Nusselt number is increased in the Negative gradients of magnetic field but it decreases in the positive gradients. It should be noted that the gradient and intensity of magnetic field determine the intensity of increase or decrease of the Nusselt number. Therefore, it can be used to control the heat transfer coefficient.

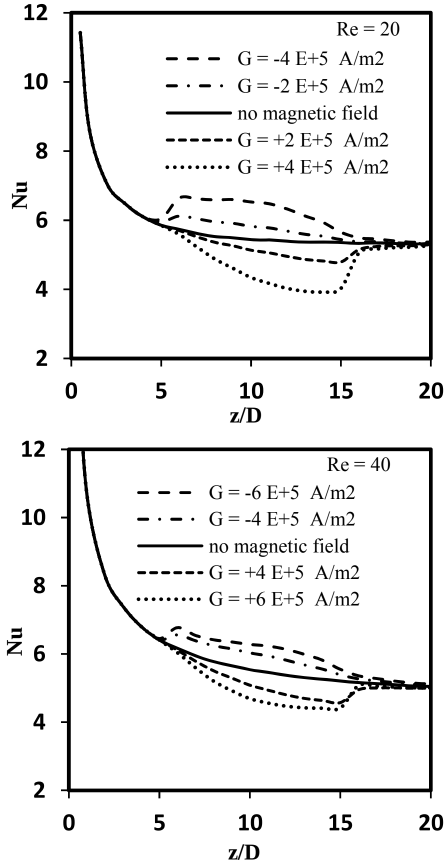

Figure 2: Effect of the various magnetic field gradients on the local Nusselt number for Re=20 and 40.

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