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CFD simulation of heat transfer in ferrofluids

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Abstract

In this work time dependent heat transfer flow through a kerosene based ferrofluid is considered. The flow is in a cylindrical geometry with the height and diameter of 10 mm. Computational fluid dynamics was used to simulate the system. In CFD simulations mixture model was applied to describe the behavior of the magnetic particles. A uniform magnetic field with different strengths and directions were used over the system. Numerical results illustrate that compare to the field free case, in the presence of magnetic field the transport processes will enhance. It was obtained when magnetic field's direction is perpendicular to the temperature gradient, heat transfer significantly will increase.

Keywords: CFD simulation, heat transfer, ferrofluid

Introduction

Ferrofluids are composed of magnetic nanoparticles and carrier fluid [1]. They are a type of functional fluids whose flow and energy transport processes can be controlled by adjusting an external magnetic field, which makes it find a variety of applications in various fields. Fore example using ferrofluids in miniaturized devices and external magnetic field enhance convection in these devices [2].

The relationship between an imposed magnetic field, the resulting ferrofluid flow and the temperature distribution is not understood well enough, and the references regarding heat transfer with magnetic fluids is relatively sparse [2]. In this work time dependent heat transfer through a ferrofluid in a cylinder under the influence of magnetic field strength was simulated.

Governing Equations

Maxwell's equations are: $\nabla.\boldsymbol{B} = 0, \nabla \times \boldsymbol{H} = 0$, where $\boldsymbol{B}$ is the magnetic induction, and $\boldsymbol{H}$ is the magnetic field vector. Using Maxwell's equations, the flux function for magnetic scalar potential, ϕ_m, may be written as

$$\nabla.\left[\left(1+\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{H}}\nabla\phi_m\right)\right]=\nabla.\left[\left(\frac{\partial \boldsymbol{M}}{\partial T}(T-T_0)+\frac{\partial \boldsymbol{M}}{\partial \alpha_p}\left(\alpha_p-\alpha_{p_0}\right)\right)\right] \tag{1}$$

where α_p, T and subscript 0 represent the volume fraction of magnetic particles, temperature and initial conditions, respectively. Within the simulations $\partial \boldsymbol{M}/\partial \boldsymbol{H}=\chi$, $\partial \boldsymbol{M}/\partial T=-\beta_m \boldsymbol{M}_0$ and $\frac{\partial M}{\partial \alpha_p}$ are constant and using Langevin equation they can be defined [3].

It is assumed that the magnetic fluid treats as a two phase mixture of magnetic particles in a carrier phase. The continuity, momentum, and energy equations for the mixture and the volume fraction equation for the secondary phases, as well as algebraic expressions for the relative velocities are solved. The governing equations are as follow:

$$\frac{\partial}{\partial t}(\rho_m)+\nabla.(\rho_m\vec{v}_m)=0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_m\vec{v}_m)+\nabla.(\rho_m\vec{v}_m\vec{v}_m)=-\nabla P_m+\mu_m\nabla^2\vec{v}_m- \\ \nabla.\left(\alpha_p\rho_p\vec{v}_{Mp}\vec{v}_{Mp}+\alpha_c\rho_c\vec{v}_{Mc}\vec{v}_{Mc}\right)+\rho_m g+\alpha_p\frac{m_p}{V_p}L(\xi)\nabla H \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_m c_{v,m}T)+\nabla.\left[\left(\alpha_p\rho_p\vec{v}_p c_{p,p}+\alpha_c\rho_c\vec{v}_c c_{p,c}\right)T\right]=\nabla.(k_m\nabla T) \tag{4}$$

where $\rho, \vec{v}, P, \mu, \xi, and\ k$ are density, velocity, pressure, dynamic viscosity, Langevin parameter and conductivity, respectively. The subscripts m, p and c refer to the mixture, magnetic particles and carrier fluid, respectively and $\vec{v}_{Mi}=\vec{v}_i-\vec{v}_m$ is diffusion velocity. From the continuity equation for secondary phase, the volume fraction equation for magnetic phase can be obtained:

$$\frac{\partial}{\partial t}(\alpha_p\rho_p)+\nabla.\left(\alpha_p\rho_p\left(\vec{v}_m-\vec{v}_{dr,p}\right)\right)=0 \tag{5}$$

where $\vec{v}_{dr,p}$ is drift velocity. With considering to forces act on a single magnetic particle, the slip velocity is defined similar to [3]

$$\vec{v}_s=\vec{v}_p-\vec{v}_c=\frac{m_p L(\xi)}{3\pi\mu d_p}\nabla H+\frac{d_p{}^2(\rho_p-\rho_c)}{18\mu}g \tag{6}$$

where d_p is the magnetic particle diameter.

Numerical Method

In this research commercial software, Fluent, was used to create the geometry and generate the grid, and a user defined function was added to apply a uniform external magnetic field parallel to the temperature gradient. To divide the geometry into discrete control volumes, about 5.9×10^5 tetrahedral computational cells, 1.2×10^6 triangular elements, and more than 10^5 nodes were used. All equations were solved using second order upwind scheme. Constant temperature boundary conditions were applied for both bottom and top of the cylinder, and uniform external magnetic field was subjected parallel to the temperature gradient.

Results and Discussion

Fig. 1(a) depicts a schematic diagram used in the present simulations and the grid is illustrated in Fig. 1(b). A kerosene-based magnetic fluid with magnetization 48 kA/m, particle diameter 9 nm, and solid volume fraction 2% was used in this study.

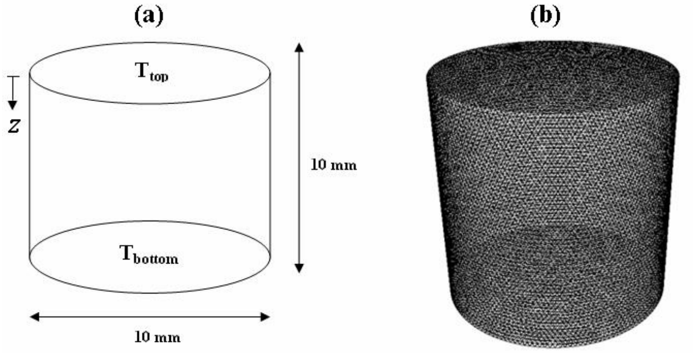

Fig. 1: (a) Schematic of the geometry, (b) The grid used in this study

The temperature difference 10 K was applied to the cylinder. The heat transfer characteristic of the ferrofluid in the presence and absence of a uniform magnetic field is given in Fig. 2. As can be expected heat flux is enhanced under an applied magnetic field. This fact confirmed experimentally by Jeyadevan et al. [4]. To investigate the effect of natural convection, a set of simulations at the same conditions, but in the absence of any convection was done. Comparison of obtained results showed that in the presence of natural convection heat transfer will increase. Since the temperature gradient in the cylinder was not very high, the difference between two conditions, with and without natural convection, was not significant.

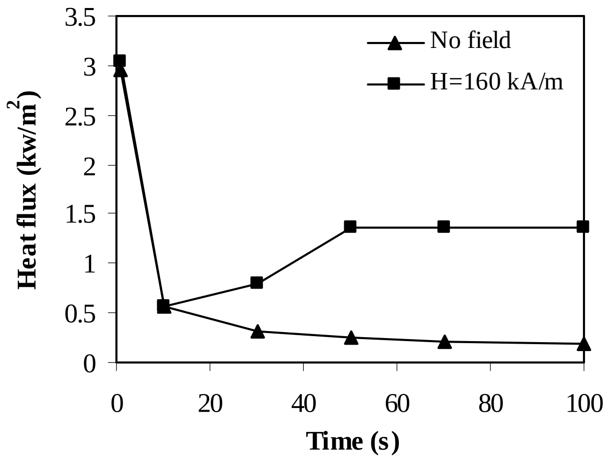

Fig. 2: Effect of magnetic field on heat flux in the presence of natural convection

To test the effect of magnetic field direction, a uniform magnetic field in parallel and perpendicular to the temperature gradient direction has been applied. The velocity profiles showed that for the second condition the velocity is higher than the situation with parallel direction to the temperature gradient. According to the results the heat transfer increases for perpendicular orientation of magnetic field and temperature gradient directions.

Conclusion

In this work CFD simulations were carried out in order to study the effect of external magnetic field on heat transfer in ferrofluids. It was found that the transferred heat is a function of magnetic field strength and its direction. Results showed that heat transfer can be increased when magnetic field and temperature gradient directions are perpendicular. The heat transfer efficiency can be further improved by optimizing the magnetic field strength, direction, and distribution.

References

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