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Effect of electric field on hydrothermal behavior of nanofluid in a complex geometry

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ABSTRACT

Electric field effect on nanofluid forced convective heat transfer in an enclosure with sinusoidal wall is presented. Control Volume based Finite Element Method (CVFEM) is utilized to simulate this problem. Fe_3O_4–ethylene glycol nanofluid is used as working fluid. Numerical investigations are conducted for several values of Reynolds number, nanoparticle volume fraction and supplied voltage. Results show that supplied voltage can change the flow shape. Coulomb force causes isotherms to be denser near the moving wall. Heat transfer rises with augmentation of supplied voltage and Reynolds number. The effect of electric field on heat transfer is more pronounced at low Reynolds number.

1. Introduction

In order to use the advantages of both finite volume and finite element methods, new numerical method has been introduced namely Control Volume based Finite Element Method (CVFEM). Multi-physics problems in complex geometries can be simulated via this powerful method ([1,2]). Sheikholeslami et al. [3] utilized an active method (magnetic field) to find the impact of Hartmann number on natural convection of nanofluid. They proved that the effect of Lorentz force is more pronounced for high Rayleigh number. Sheikholeslami and Rashidi [4] investigated the impact of space dependent magnetic field on hydrothermal treatment of Fe_3O_4–water nanofluid. Their results verified that Lorentz force causes Nusselt number to reduce due to retarding flow. Sheikholeslami et al. [5] presented the impact of applying a constant magnetic field on nanofluid hydrothermal behavior in a cavity heated from below. They proved that the influence of Hartmann number and heat source augments with an increase of Rayleigh number. This method was successfully applied in different problems [6–19].

One of the important active methods for improving rate of heat transfer is utilizing an electric field. The influence of electric field on buoyancy-induced flow was studied by Shu and Lai [20]. In their study electrodynamic equations are separated from fluid dynamic equations. The influence of electrode arrangements on rate of heat transfer was studied by Kasayapanand et al. [21]. The effect of electric field on fluid flow over a plate has been investigated by Velkoff and Godfrey [22]. Mathematical and numerical modeling of electrohydrodynamic (EHD) enhancement of natural convection in enclosures was carried out by Yan et al. [23]. They found that applying a non-uniform electric field offers better enhancement of heat transfer than applying a uniform electric field. Bararnia and Ganji [24] used lattice Boltzmann method to simulate deformation and breakup of a falling drop under gravity and electric field. They found that drop distorts more by increasing the Eotvos number and decreasing Ohnesorge number. The behavior of water droplets which were suspended in silicon oil was qualitatively investigated by Bararnia and Ganji [25]. They observed any deformation caused by increasing voltage from start to finish until short contact occurred.

In order to improve the thermophysical characteristics of base fluid, nano-scale metal can be added in the base fluid. In which way, thermal conductivity of fluid rises and in turn heat transfer can be enhanced. Khanafer et al. [26] used finite volume method to simulate nanofluid hydrothermal improvement. They indicated that adding nanoparticles leads to a rise in Nusselt number. Rahman et al. [27] investigated

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Nomenclature

b	ironic mobility
D_e, D	diffusion number $(=\mu_0/(\rho_0 D_0))$, charge diffusion coefficient
Ec	Eckert number $(=\rho_f {U_{Lid}}^2/((\rho C_p)_f(T_1-T_0)))$
$\overrightarrow{E},\ E_x,\ E_y$ electric field	
$\overrightarrow{F_E}$	Coulomb force
$\overrightarrow{J}$	electric current density
L	characteristic length
N_E	electric field number $(=q_0L^2/(\varepsilon\Delta\varphi))$
p	pressure
PR	Prandtl number $(=\upsilon_f/\alpha_f)$
Pr_E	electric Prandtl number $(=\mu_f/(\rho_f b\Delta\varphi))$
q	electric charge density
Re	Reynolds number $(=\rho_f U_{Lid}L/\mu_f)$
S_E	Lorentz force number $(=q_0\Delta\varphi/(\rho {U_{Lid}}^2))$
t	time
T	temperature
u,v	Cartesian components of velocity $\overrightarrow{V}$
Greek symbols	
ε	dielectric permittivity
β	coefficient of expansion
ϕ	Volume fraction
μ	Dynamic viscosity
ρ	Density
σ	electric conductivity
φ	electric field potential
Subscripts	
ave	average
c	cold
s	solid particles
f	base fluid
h	hot
nf	nanofluid

nanofluid hydrothermal treatment in a tilted enclosure with moving wall. They showed that temperature enhances with a rise of nanofluid volume fraction. Combined nanofluid free and force convection heat transfer in an enclosure with moving wall has been studied by Rahman et al. [28]. They verified that rate of improvement is more pronounced at higher tilt angle. Sheikholeslami Kandelousi [29] studied the nanofluid hydrothermal behavior in a porous channel. He showed that Nusselt number rises with augmentation of Reynolds number when power law index is equal to zero. Sheikholeslami and Abelman [30] utilized two phase model for analysis of nanofluid flow and heat transfer in an annulus in the presence of an axial magnetic field. Nanofluid hydrothermal treatment between two horizontal parallel plates in a rotating system was studied by Sheikholeslami et al. [31]. They proved that Nusselt number enhances with a rise of Reynolds number and nanoparticle volume fraction but it decreases with an increase of magnetic, rotation parameters and Eckert number. Sheikholeslami and Ellahi [32] studied three dimensional mesoscopic simulation of magnetic field effect on natural convection of nanofluid. They found that thermal boundary layer thickness increases with an increase of Lorentz forces. Nanofluid and other passive techniques were studied by several authors [33–81].

The main purpose of this paper is to investigate electrohydrodynamic nanofluid flow and forced convective heat transfer via CVFEM. Influences of supplied voltage and Reynolds number on flow and heat transfer have been examined.

2. Problem definition

Fig. 1 illustrates the physical geometry along with the important parameters and mesh of the enclosure. The lower wall has the velocity of U_{Lid} and others are stationary. The lower wall has constant temperature T_1 and the temperature of other walls is T_0. Also the retained boundary conditions are depicted in Fig. 1(a). The shape of inner cylinder profile is assumed to mimic the following pattern:

$$r = r_{in} + A\cos(N(\zeta)) \tag{1}$$

in which r_{in} is the base circle radius, r_{out} is the radius of outer cylinder, A and N are the amplitude and number of undulations, respectively. ζ is the rotation angle. In this study A and N equal to 0.025 and 48, respectively. Fig. 2 depicts the distribution of electric density for different Reynolds numbers and supplied voltage.

3. Governing equations

3.1. Mathematical model

In order to simulate nanofluid hydrothermal treatment in the existence of electric field, we should combine equations of electric field with those of hydrothermal. The formulas of electric field are:

$$\nabla\cdot\left(\overrightarrow{E}\,\varepsilon\right) = q \tag{2}$$

$$(-\nabla\varphi) = \overrightarrow{E} \tag{3}$$

$$\nabla\cdot\overrightarrow{J} + \frac{\partial q}{\partial t} = 0. \tag{4}$$

There exist two models for charge distribution: (1) conductivity model [82–83] and (2) mobility model [84]. In the first model, electro-convection relies on temperature gradient. But in the second model, electro-convection is independent of temperature gradient in the liquid. In the case of free charge origination, the second model is more acceptable according to the experimental results. Electric current density can be defined as [85]:

$$\overrightarrow{J} = \sigma\overrightarrow{E} - D\nabla q + q\overrightarrow{V} \tag{5}$$

where $\sigma\overrightarrow{E}$ is the ionic mobility, $D\nabla q$ is the diffusion [86], and $q\overrightarrow{V}$ is the convection.

According to Eqs. (4) and (5), the equation for electric charge density can be obtained as follows:

$$\frac{\partial \bar{q}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{q}}{\partial \bar{y}} + \bar{u}\frac{\partial \bar{q}}{\partial \bar{x}} + \frac{1}{\mathrm{Re}\,\mathrm{Pr}_E}\left[\bar{q}\left(\frac{\partial \bar{E}_y}{\partial \bar{y}} + \frac{\partial \bar{E}_x}{\partial \bar{x}}\right) + \bar{E}_y\frac{\partial \bar{q}}{\partial \bar{y}} + \bar{E}_x\frac{\partial \bar{q}}{\partial \bar{x}}\right] = \frac{\rho_{nf}/\rho_f}{\mu_{nf}/\mu_f}\frac{1}{\mathrm{Re}D_e}\left(\frac{\partial^2 \bar{q}}{\partial \bar{y}^2} + \frac{\partial^2 \bar{q}}{\partial \bar{x}^2}\right). \tag{6}$$

According to [85] the diffusion term can be taken negligible. Also $D\nabla q$ in Eq. (5) can be taken negligible and $\sigma = bq$ [86]. So Eq. (5) can be considered as:

$$\overrightarrow{J} = q\overrightarrow{V} + qb\overrightarrow{E}. \tag{7}$$