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Numerical simulation of thermal radiative heat transfer effects on Fe_3O_4-ethylene glycol nanofluid EHD flow in a porous enclosure

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KEYWORDS

Electric field;
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Nanofluid;
Porous media;
Thermal radiation.

Abstract. Electrohydrodynamic Fe_3O_4-Ethylene glycol nanofluid forced convection was simulated in presence of thermal radiation. The porous lid driven cavity had one moving positive electrode. A single-phase model was applied to simulate nanofluid behavior. Control volume based finite element method was employed to obtain the results, which showed the roles of Darcy number (Da), radiation parameter (Rd), Reynolds number (Re), nanofluid volume fraction (ϕ), and supplied voltage ($\Delta\varphi$). Results depicted that maximum values of the temperature gradient were obtained for platelet-shape nanoparticles. Nusselt number was enhanced with increase in Darcy number and supplied voltage. Convection mode rose with increase in permeability of porous media and nanofluid volume fraction, but it decreased with the rise in Hartmann number.

1. Introduction

One of the effective active techniques for heat transfer augmentation is Electrohydrodynamic. Rarani et al. [1] reported good correlation for viscosity of nanofluid. Nanofluid has various applications in presence of various external forces [2,3]. Three-dimensional nanofluid flows were studied by Sheikholeslami and Ellahi [4]. They illustrated that velocity decreased with the augmentation of Lorentz forces. Sheikholeslami and Ganji [5] studied the nanofluid flow in a porous channel in presence of Lorentz forces. Sheikholeslami and Shehzad [6] presented the influence of radiative mode on ferrofluid motion. They took variable viscosity into account. Nanofluid concentration was surveyed by Hayat et al. [7] in radiative mode. Sheikholeslami and Seyednezhad [8] utilized CVFEM for nanofluid natural convection in presence of electric field in a porous cavity. Sheikholeslami et al. [9] investigated nanofluid intensification in a curved porous cavity considering various shapes of nanoparticles.

Conjugate heat transfer of nanofluid was studied by Selimefendigil and Oztop [10]. They considered various inclination angles. Sheikholeslami et al. [11] simulated MHD nanofluid forced convection by means of LBM. Sheikholeslami and Rokni [12] addressed the nanofluid behavior under the effect of Coulomb force in a porous cavity. Sheikholeslami [13] presented a mesoscopic simulation of nanofluid convective flow in presence of magnetic field. Effect of variable Kelvin forces on ferrofluid motion was simulated by Sheikholeslami

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Kandelousi [14]. Heat flux boundary condition was utilized by Sheikholeslami and Shehzad [15] to investigate the ferrofluid flow in porous media. Nanoparticle movement in a channel due to Lorentz forces was demonstrated by Akbar et al. [16]. Sheikholeslami et al. [17] examined nanoparticle transportation under the impact of thermal radiation. In recent decades, various researchers have published papers on heat transfer [18-32].

This study intends to model the influence of thermal radiation on nanofluid behavior in presence of Coulomb forces via CVFEM. Roles of Darcy number, Reynolds number, supplied voltage, radiation parameter, and Fe_3O_4 volume fraction are presented in outputs.

2. Problem definition

Figure 1 depicts the porous enclosure and its boundary conditions. Ethylene glycol-Fe_3O_4 nanofluid is utilized. All walls are stationary except for the bottom wall. Influence of Darcy and Reynolds numbers on contour of q is demonstrated in Figure 2. As observed, the effect of Re on q is less sensible than that of Da. As Darcy number increases, the distortion of isoelectric density lines becomes more.

3. Governing formulae and modeling

3.1. Governing formulae

The definition of electric field is [33]:

$$\vec{E} = -\nabla\varphi, \tag{1}$$

$$q = \nabla.\varepsilon\vec{E}, \tag{2}$$

$$\vec{J} = q\vec{V} - D\nabla q + \sigma\vec{E}, \tag{3}$$

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

The governing formulae are [33]:

$$\begin{aligned}
&\nabla.\vec{V} = 0,\\
&\left(\left(\vec{V}.\nabla\right)\vec{V} + \frac{\partial\vec{V}}{\partial t}\right) = \frac{q\vec{E}}{\rho_{nf}} + \frac{\mu_{nf}}{\rho_{nf}}\nabla^2\vec{V}\\
&\qquad -\frac{\nabla p}{\rho_{nf}} - \frac{\mu_{nf}}{K\rho_{nf}}\vec{V},\\
&\left(\left(\vec{V}.\nabla\right)T + \frac{\partial T}{\partial t}\right) = \frac{k_{nf}}{(\rho C_p)_{nf}}\nabla^2 T\\
&\qquad +\frac{\vec{J}.\vec{E}}{(\rho C_p)_{nf}} - \frac{1}{(\rho C_p)_{nf}}\frac{\partial q_r}{\partial y},\\
&\left[q_r = -\frac{4\sigma_e}{3\beta_R}\frac{\partial T^4}{\partial y},\quad T^4 \cong 4T_c^3 T - 3T_c^4\right],\\
&\nabla\varphi = -\vec{E},\\
&\frac{\partial q}{\partial t} = -\nabla.\vec{J},\\
&q = \nabla.\varepsilon\vec{E}.
\end{aligned} \tag{5}$$

$(\rho C_p)_{nf}$, μ_{nf}, and ρ_{nf} can be obtained as [34]:

$$(\rho C_p)_{nf} = (\rho C_p)_f(1-\phi) + (\rho C_p)_s\phi,$$

$$\mu = A_1 + A_2(\Delta\varphi) + A_3(\Delta\varphi)^2 + A_4(\Delta\varphi)^3,$$

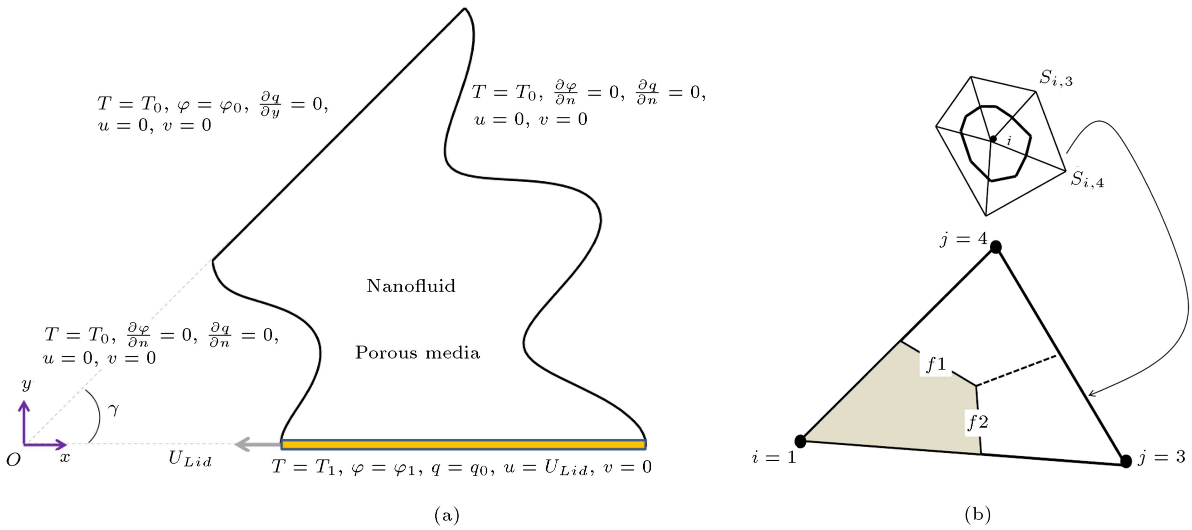


Figure 1. (a) Geometry and the boundary conditions with (b) a sample triangular element and its corresponding control volume.

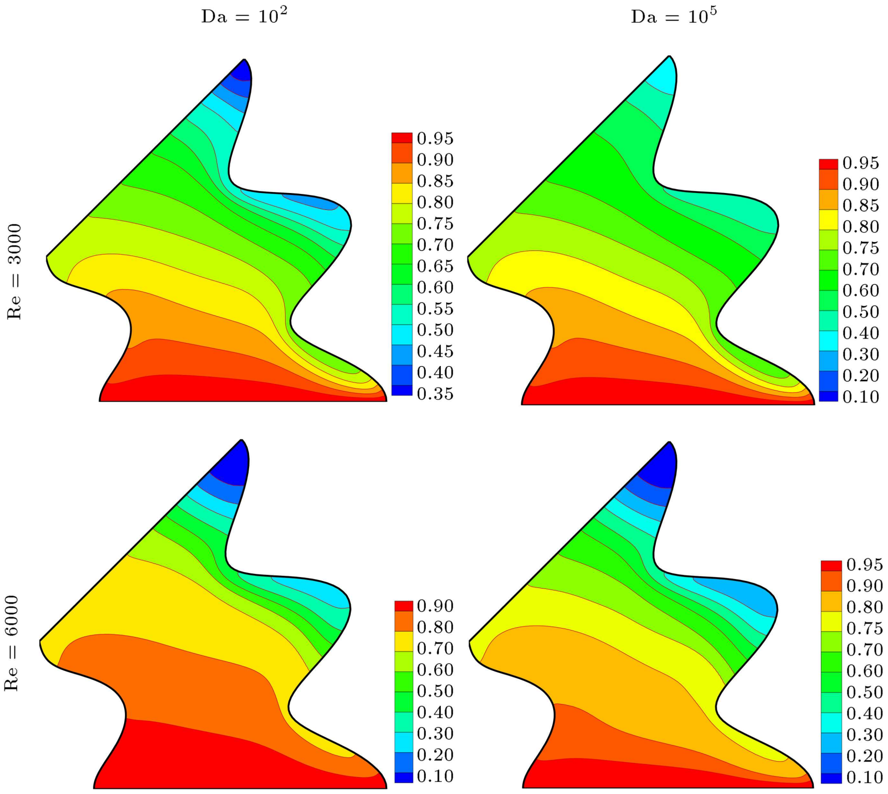


Figure 2. Electric density distribution injected by the bottom electrode when $\Delta\varphi = 10$ kV, $\phi = 0.05$, and $Rd = 0.8$.

$$\rho_{nf} = \rho_f(1-\phi) + \rho_s\phi. \tag{6}$$

Properties of Fe_3O_4 and ethylene glycol are illustrated in Table 1 [1]. EFD viscosity is presented by Monajjemi Rarani et al. [1]. Table 2 illustrates the values of coefficients for this formula. k_{nf} can be expressed as:

$$\frac{k_{nf}}{k_f} = \frac{-m\left(k_f - k_p\right)\phi + \left(k_p - k_f\right)\phi + mk_f + k_p + k_f}{mk_f + \left(k_f - k_p\right)\phi + k_f + k_p}. \tag{7}$$

Different values of shape factors for various shapes of nanoparticles are illustrated in Table 3.

Thus, the final PDE in presence of thermal

Table 1. Thermo-physical properties of ethylene glycol and nanoparticles.

	ρ (kg/m^3)	C_p (J/kgk)	k (W/m.k)
Ethylene glycol	1110	2400	0.26
Fe_3O_4	5200	670	6

Table 2. The values of coefficients for Eq. (6).

Coefficient values	$\phi = 0$	$\phi = 0.05$
A_1	1.0603E+001	9.5331
A_2	-2.698E-003	-3.4119E-003
A_3	2.9082E-006	5.5228E-006
A_4	-1.1876E-008	-4.1344E-008

Table 3. The values of shape factors for different shapes of nanoparticles.

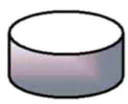
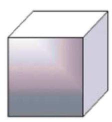
	Spherical		3
m	Platelet		5.7
	Cylinder		4.8
	Brick		3.7

Table 4. Comparison of values of Nu_{ave} along lid wall for different grid resolutions at $Rd = 0.8$, Re = 6000, Da = 10^5, $\Delta\varphi = 10$, $\phi = 0.05$, and Pr = 6.8.

51×151	61×181	71×211	81×241	91×271	101×301
6.827544	6.835511	6.838134	6.841524	6.842627	6.843308

radiation and electric field in porous media is:

$$\nabla.\vec{V} = 0,$$

$$\left(\left(\vec{V}.\nabla\right)\vec{V} + \frac{\partial\vec{V}}{\partial t}\right) = \frac{1}{\mathrm{Re}}\frac{\rho_{nf}/\rho_f}{\mu_{nf}/\mu_f}\nabla^2\vec{V}$$

$$-\nabla p + \frac{S_E}{\rho_{nf}/\rho_f}q\vec{E} - \frac{1}{\mathrm{Re}\,\mathrm{Da}}\frac{\mu_{nf}}{\mu_f}\left(\frac{\rho_{nf}}{\rho_f}\right)^{-1}\vec{V},$$

$$\left(\left(\vec{V}.\nabla\right)\theta + \frac{\partial\theta}{\partial t}\right) = \frac{1}{\mathrm{PrRe}}\frac{k_{nf}/k_f}{(\rho C_p)_{nf}/(\rho C_p)_f}\nabla^2\theta$$

$$+S_E\frac{1}{(\rho C_p)_{nf}/(\rho C_p)_f}Ec\left(\vec{J}.\vec{E}\right)$$

$$+\frac{4}{3}\left(\frac{k_{nf}}{k_f}\right)^{-1}Rd\frac{\partial^2\theta}{\partial Y^2},$$

$$\vec{E} = -\nabla\varphi,$$

$$q = \nabla.\varepsilon\vec{E},$$

$$\nabla.\vec{J} = -\frac{\partial q}{\partial t}, \tag{8}$$

where,

$$(\bar{u},\bar{v}) = \frac{(u,v)}{U_{Lid}}, \quad \bar{\varphi} = \frac{\varphi - \varphi_0}{\nabla\varphi}, (\bar{y},\bar{x}) = \frac{(y,x)}{L},$$

$$\theta = \frac{T - T_0}{\nabla T}, \quad \bar{t} = \frac{tU_{Lid}}{L}, \quad \bar{p} = \frac{P}{\rho {U_{Lid}}^2},$$

$$\bar{q} = \frac{q}{q_0}, \quad \bar{E} = \frac{E}{E_0}, \quad \nabla T = T_1 - T_0,$$

$$\nabla\varphi = \varphi_1 - \varphi_0. \tag{9}$$

Vorticity and stream function should be employed in order to diminish pressure gradient:

$$v = -\frac{\partial\psi}{\partial x}, \quad \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad \frac{\partial\psi}{\partial y} = u,$$

$$\Psi = \frac{\psi L}{U_{Lid}}, \Omega = \frac{\omega}{LU_{Lid}}. \tag{10}$$

Nu_{loc} and Nu_{ave} along the bottom wall are calculated as:

$$\mathrm{Nu}_{loc} = \left(\frac{k_{nf}}{k_f}\right)\left(1 + \frac{4}{3}Rd\left(\frac{k_{nf}}{k_f}\right)^{-1}\right)\frac{\partial\Theta}{\partial X}, \tag{11}$$

$$\mathrm{Nu}_{ave} = \frac{1}{L}\int_0^L \mathrm{Nu}_{loc}\,dY. \tag{12}$$

3.2. CVFEM

CVFEM uses the benefits of both common CFD methods. This method uses triangular element (see Figure 1(b)). Upwind approach is utilized for the advection term. Gauss-Seidel method is applied to find the solution to the algebraic system. Further notes exist in [35].

4. Mesh study and code validation

Different mesh sizes were tested to find the mesh independent result. Table 4 demonstrates an example. This table indicates that the size of 81 × 241 can be selected. The CVFEM code was validated by comparing the outputs with those reported in [34] and [36] (see Figure 3). Good agreement was found.

5. Results and discussion

Thermal radiation impact on nanofluid forced convection in presence of electric field was investigated by means of CVFEM. The porous enclosure was filled with Fe_3O_4-ethylene glycol and had one lid wall. EFD viscosity was taken into account for nanofluid. Roles of Darcy number (Da = 10^2 to 10^5), Radiation parameter ($Rd = 0$ to 0.8), supplied voltage ($\Delta\varphi = 0$ to 10 kV), volume fraction of Fe_3O_4 (ϕ = 0% to 5%), and Reynolds number (Re = 3000 to 6000) were addressed.

Effect of shape factor on Nusselt number is simulated in Table 5. In this table, various shapes of nanoparticles are utilized. The maximum Nu is

Table 5. Effect of shape of nanoparticles on Nusselt number when $Rd = 0.8$, Re = 6000, $\Delta\varphi = 10$, and $\phi = 0.05$.

	Da	
	$\mathbf{10^2}$	$\mathbf{10^5}$
Spherical	5.243563	6.596998
Brick	5.298611	6.665156
Cylinder	5.379728	6.765308
Platelet	5.441616	6.841524

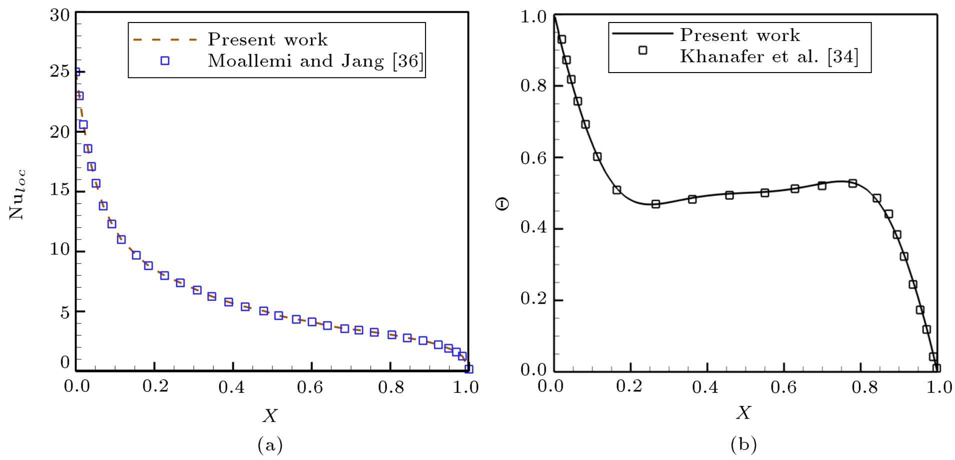


Figure 3. (a) Comparison between the local Nusselt numbers over the lid wall in the present results and those of Moallemi and Jang [36] at Re = 500, $R_i = 0.4$, and Pr = 1. (b) Comparison between temperature profiles of the present results and the numerical results of Khanafer et al. [34] for Gr = 10^4, $\phi = 0.1$ and Pr = 6.8 (Cu-water).

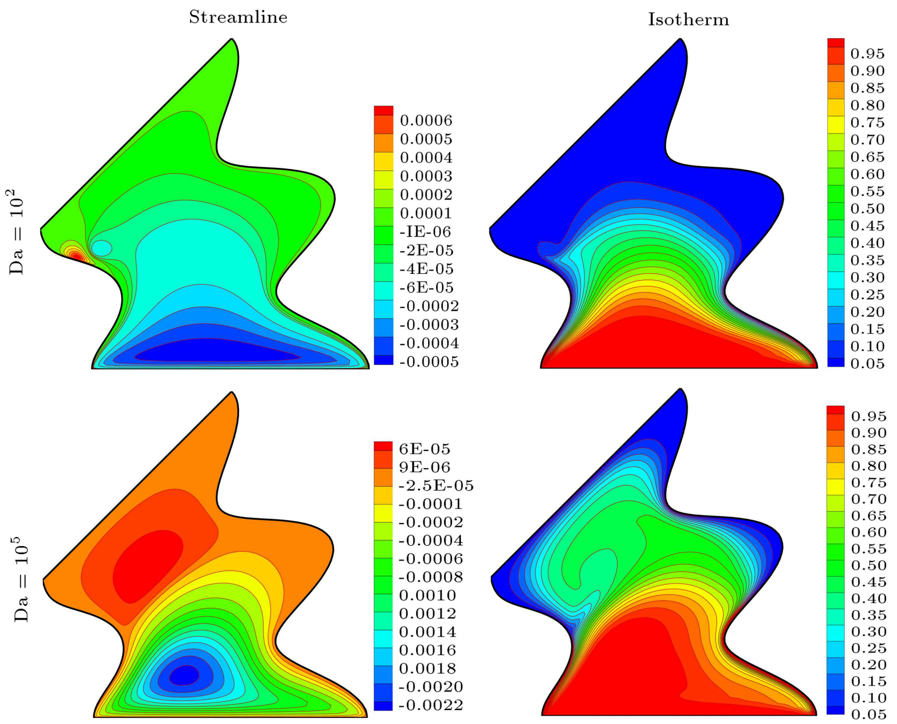


Figure 4. Effect of Darcy number on streamlines and isotherm when Re = 3000, $\Delta\varphi = 0$ kV, $\phi = 0.05$, and $Rd = 0.8$.

achieved by $m = 5.7$. Therefore, platelet nanoparticle will be utilized for further investigation.

Figures 4, 5, and 6 show isotherm and streamlines for various values of Da, $\Delta\varphi$, and Re. When Re = 3000, the center of the main eddy is near the bottom wall. As Darcy number increases, the center of the main eddy shifts to wavy wall and a new secondary rotating vortex is generated. Thus, isotherms become more complex in high values of Darcy number. Applying electric field causes $\psi_{\max}$ to increase and shift the center of the eddy to the upper region. Shape of isotherms becomes complex when electric field increases and thermal plume is generated. Also, by increasing Re, $\psi_{\max}$ increases. As Coulomb force increases, the strength of the main eddy increases and stronger thermal plume appears.

Nu_{ave} versus Re, Da, Rd, and $\Delta\varphi$ is depicted in Figure 7. The associated formula is:

$$\mathrm{Nu}_{ave} = -0.99 + 0.06\Delta\varphi + 1.5\mathrm{Re}^* + 0.75\log(\mathrm{Da}) + 5.07Rd - 0.015\Delta\varphi\mathrm{Re}^* + 0.012\Delta\varphi\log(\mathrm{Da})$$

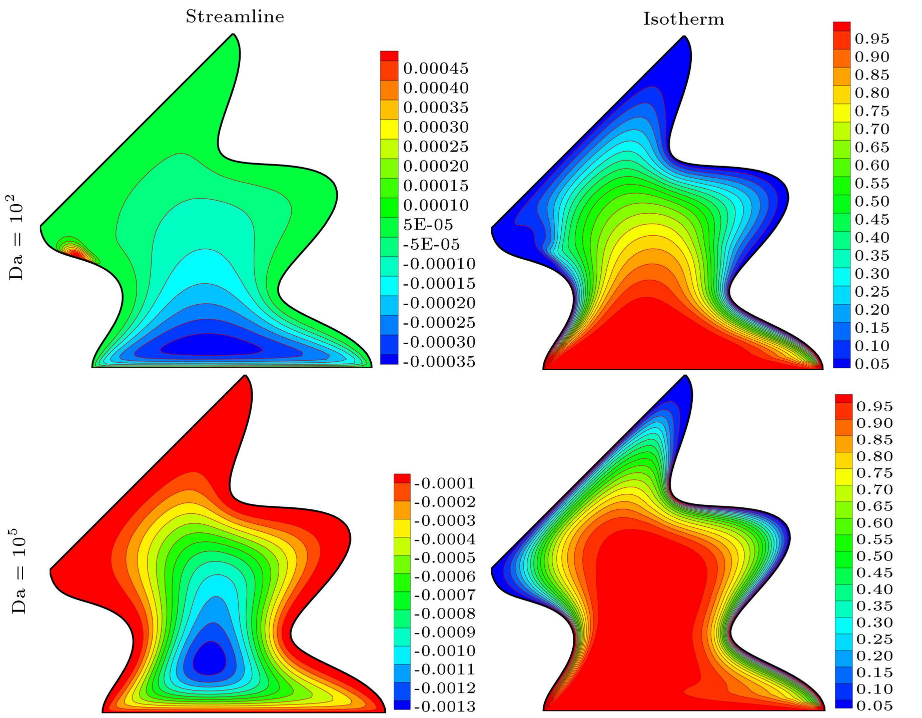


Figure 5. Effect of Darcy number on streamlines and isotherm when Re $= 3000$, $\Delta\varphi = 10$ kV, $\phi = 0.05$, and $Rd = 0.8$.

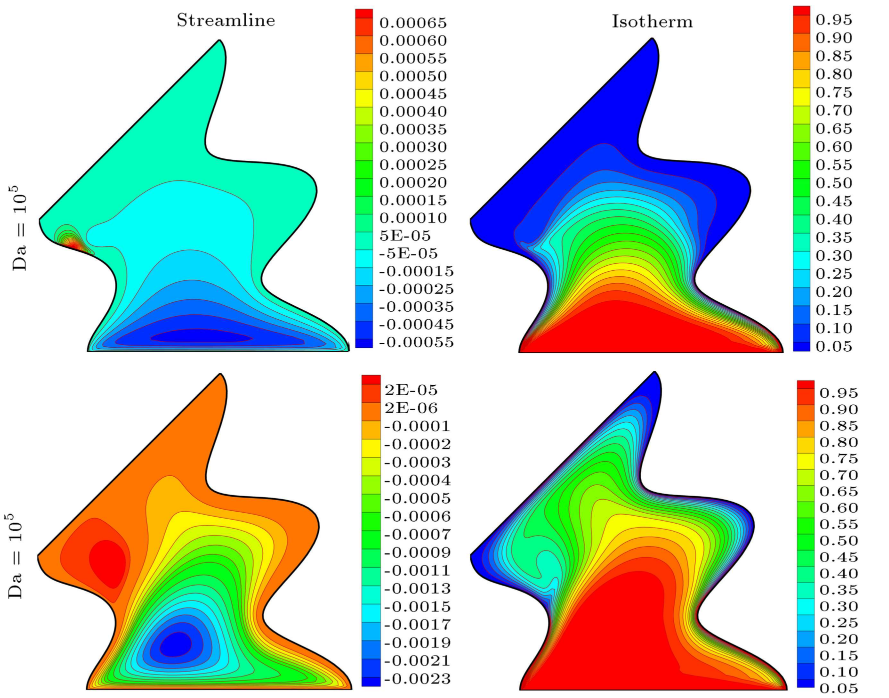


Figure 6. Effect of Darcy number on streamlines and isotherm when Re $= 6000$, $\Delta\varphi = 10$ kV, $\phi = 0.05$, and $Rd = 0.8$.

$$-0.03\Delta\varphi Rd - 0.09\mathrm{Re}^{*}\log(\mathrm{Da})$$

$$-1.53\mathrm{Re}^{*}Rd + 0.45\log(\mathrm{Da})\,Rd + 0.006\Delta\varphi^{2}$$

$$-0.16(\mathrm{Re}^{*})^{2} - 0.015(\log(\mathrm{Da}))^{2} + 0.01Rd^{2}, \quad (13)$$

where $\mathrm{Re}^{*} = 0.001$ Re and $\Delta\varphi$ is voltage supply in kilovolts. In presence of Coulomb force, Nusselt number decreases with the rise of the Reynolds number. Electric field helps the convective mode to increase. Therefore, Nu_{ave} increases with increase in $\Delta\varphi$. As

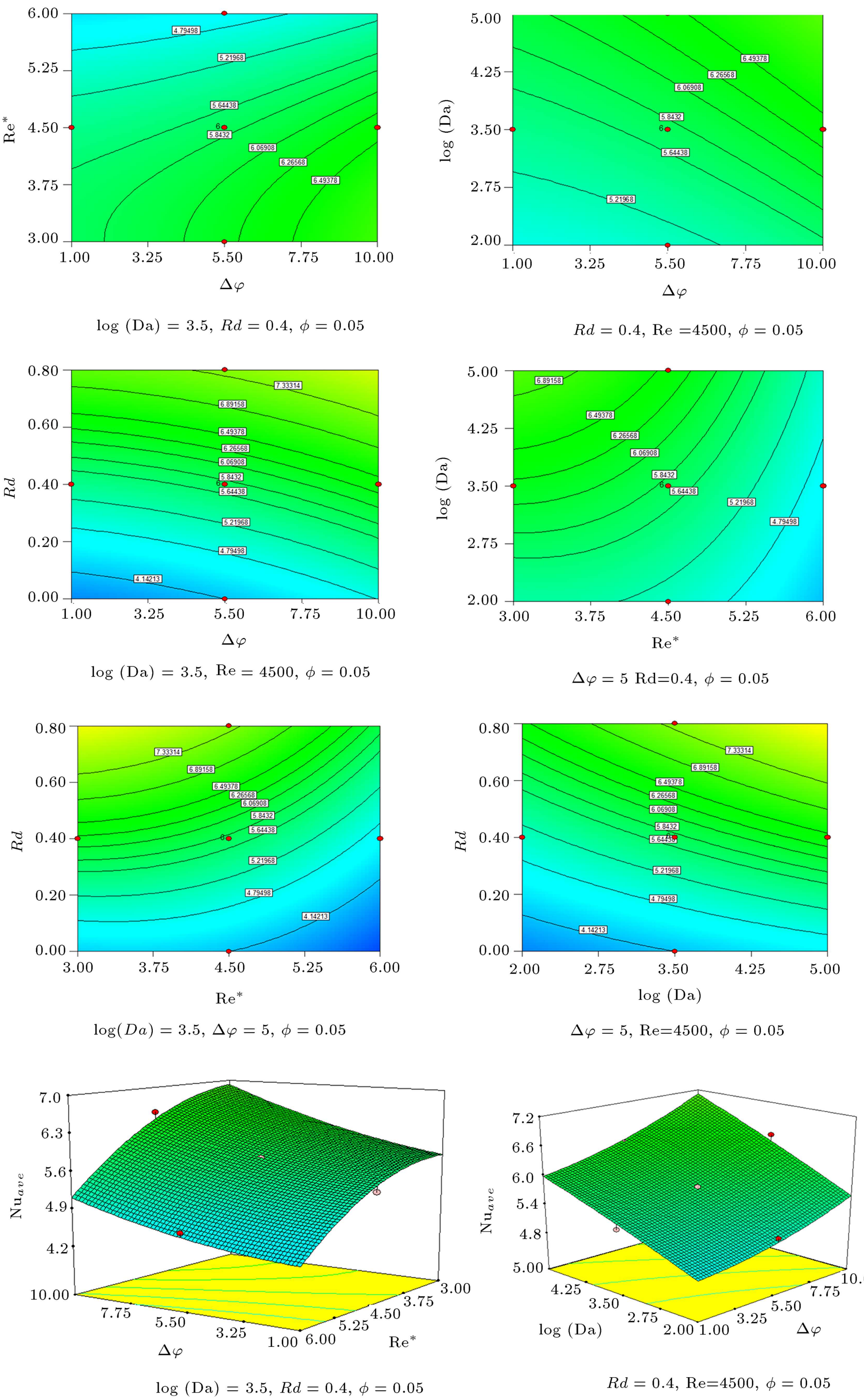


Figure 7. Effects of Da, $\Delta\varphi$, Rd, and Re on average Nusselt number.

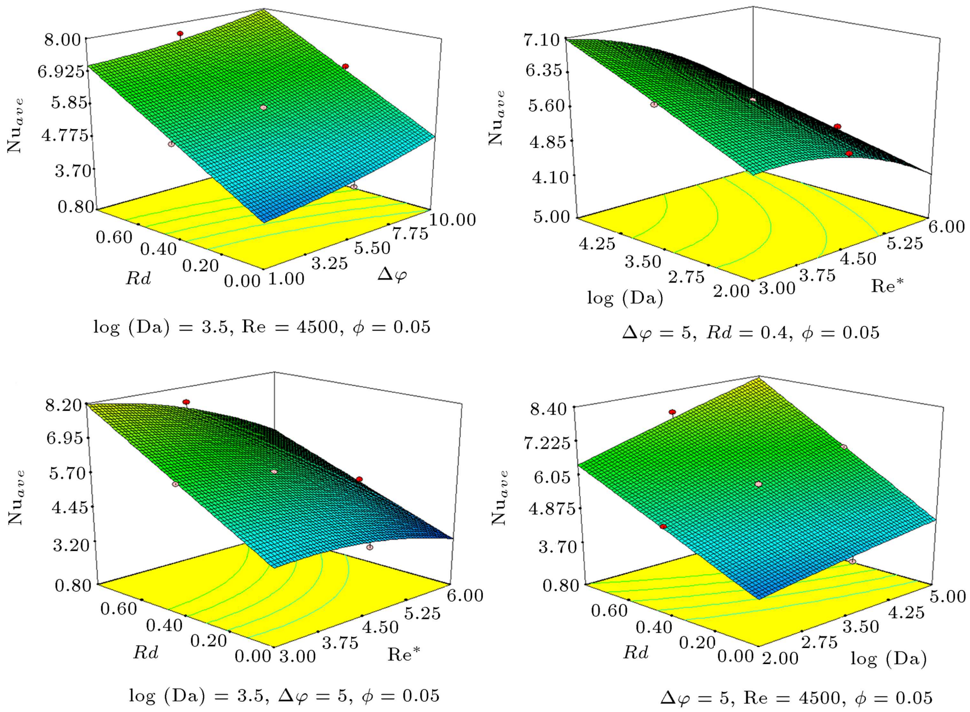


Figure 7. Effects of Da, $\Delta\varphi$, Rd, and Re on average Nusselt number (continued).

Rd rises, the temperature gradient near the hot wall increases. Influence of Darcy number is same as that of radiation parameter. Thus, Nu_{ave} is an increasing function of Rd, Da.

6. Conclusions

Effect of Coulomb forces on nanofluid laminar convective heat transfer in a lid driven porous enclosure in presence of thermal radiation was simulated by means of CVFEM. Outputs were reported for various values of Da, Rd ϕ, $\Delta\varphi$, and Re. Outputs demonstrated that the distortion of isotherms increased with the rise of radiation parameter, Darcy number, and Coulomb forces. Increasing Coulomb forces made the secondary eddy diminish. Nusselt number increases with the rise of radiation parameter.

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Nomenclature

S_E	Lorentz force number
D_e	Diffusion number
v, u	Vertical and horizontal velocities
$\overrightarrow{F_E}$	Electric force
N_E	Electric field number
Re	Reynolds number
Pr_E	Electric Prandtl number
$\overrightarrow{E}, E_x, E_y$	Electric field

Greeksymbols

ϕ	Volume fraction
ρ	Density
σ	Electric conductivity
μ	Dynamic viscosity
φ	Electric field potential

Subscripts

s	Solid particles
f	Base fluid
c	cold
nf	Nanofluid
h	Hot

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Biographies

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