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TECHNICAL PAPER

Numerical approach for nanofluid transportation due to electric force in a porous enclosure

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Abstract

In current attempt, nanoparticle Electrohydrodynamic transportation has been modeled numerically via control volume based finite element method. Mixture of Fe_3O_4 and Ethylene glycol is elected. Impact of radiation parameter (Rd), voltage supplied ($\Delta\varphi$), nanoparticle concentration, Permeability and Reynolds number have been displayed. Results display that permeability and thermal radiation can improve temperature gradient.

List of symbols

N_E	Electric field number
$\vec{F_E}$	Electric force
u	Horizontal velocity
D_e	Diffusion number
S_E	Lorentz force number
Pr_E	Electric Prandtl number

Greek symbols

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

Subscripts

c	Cold
s	Solid particles

1 Introduction

To overcome low conduction of working fluid, nanofluid has been suggested in last years. Mishra and Bhatti (2017) demonstrated Ohmic heating impact on fluid behavior considering chemical reaction. Sheikholeslami et al. (2018a) displayed the nanoparticle migration in permeable media with Darcy model when the domain is affected by magnetic force. Sheikholeslami and Bhatti (2017) investigated external force influence on heat transfer behavior of nanoparticles. Sheikholeslami and Rokni (2018a) displayed nanoparticle transportation because of Lorentz forces in a porous annulus. Bhatti et al. (2017) displayed movement of nanofluid with microorganism because of Lorentz forces. Sheikholeslami (2018a) displayed an application of FEM for discharging process of NEPCM. Bhatti et al. (2016) displayed the migration of titanium nanoparticles in blood flow with low velocity. Eldabe et al. (2018) illustrated motion of working fluid over moving sheet. They simulated the problem in two dimension and considered magnetic force impact. Bhatti et al. (2017) simulated EMHD

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pumping of viscoelastic fluid considering nonlinear radiation. Sheikholeslami and Bhatti (2017b) displayed the influence of nanoparticles' shape on heating characteristics. Sheikholeslami (2018b) depicted the nanofluid movement in a porous enclosure with Darcy law. Ramzan et al. (2017) demonstrated activation energy influence on radiation heat transfer of nanofluid. They also considered binary chemical reaction and buoyancy forces impacts. Sheikholeslami et al. (2018b) utilized Lorentz forces to accelerate discharging process. They simulated porous heat storage. Sheikholeslami et al. (2018c) depicted the nanofluid exergy loss through a duct with twisted tape. Challenge of finding best working fluid was discussed in various papers (Sheikholeslami et al. 2018d, e, f, g, h, i, j, k, l, m, n, o; Sheikholeslami 2017e, f, g, 2018c, d, e, f, g, h, i, j, k; Bhatti and Ali 2016; Bhatti et al. 2017c, d; Eldabe et al. 2018b; Khan et al. 2018; Sheikholeslami and Ghasemi 2018; Sheikholeslami and Shehzad 2018a, d; Sheikholeslami and Rokni 2017a, b, c, d, e, 2018b; Zeeshan et al. 2018; Sheikholeslami and Shehzad 2018a, b; Besthapu et al. 2017; Sheikholeslami and Seyednezhad 2018; Sheikholeslami and Sadoughi 2018; Sheikholeslami and Seyednezhad 2017a, b; Sheikholeslami and Shehzad 2017a; Sheikholeslami and Sadoughi 2017a; Haque et al. 2013; Ramzan et al. 2017b; Ramzan et al. 2016; Ellahi et al. 2014; Sheikholeslami and Ellahi 2015a; b; Sheikholeslami et al. 2015; Sheikholeslami and Rokni 2017c; Sheikholeslami 2017a; Sheikholeslami and Shehzad 2017b; Sheikholeslami and Sadoughi 2017b; Sheikholeslami 2017b, c, d; Sheikholeslami and Zeeshan 2017; Sheikholeslami and Vajravelu 2017; Sheikholeslami and Shehzad 2017; Sheikholeslami and Chamkha 2017; Dianchen 2017, 2018; Ahmed 2017; Ellahi et al. 2016; Abro 2017; Shahid et al. 2017; Mehmood et al. 2017).

In current text, electric forces influences on nanofluid treatment in a permeable medium are discussed. CVFEM was employed to display the impact voltage; Reynolds number, radiation parameter, and concentration of Fe_3O_4.

2 Problem explanation

As displayed in Fig. 1, a porous geometry in existence of external forces was considered. Figure 2 depicts contour plots of q. Darcy number has impressive impact on q.

3 Formulation and simulation

3.1 Formulation

$\vec{E}$ can be calculated (Sheikholeslami and Bhatti 2017):

$$\vec{J} = q\vec{V} + \sigma\vec{E} - D\nabla q, \tag{1}$$

$$\nabla\cdot\vec{J} = -\frac{\partial q}{\partial t}, \tag{2}$$

$$q = \nabla\cdot\varepsilon\vec{E}, \tag{3}$$

$$\vec{E} = -\nabla\varphi. \tag{4}$$

Formulation of current problem is (Sheikholeslami and Bhatti 2017):

$$\begin{cases} \nabla\cdot\vec{V} = 0, \\ -\upsilon_{nf}\frac{\vec{V}}{K} + \upsilon_{nf}\nabla^2\vec{V} = \frac{\nabla p}{\rho_{nf}} + \left(\left(\vec{V}\cdot\nabla\right)\vec{V} + \frac{\partial\vec{V}}{\partial t}\right) - \frac{q\vec{E}}{\rho_{nf}}, \\ -\left(\rho C_p\right)_{nf}^{-1}\nabla^2 T\,k_{nf} + \left(\frac{\partial T}{\partial t} + \left(\vec{V}\cdot\nabla\right)T\right) + \left(\rho C_p\right)_{nf}^{-1}\frac{\partial q_r}{\partial y} = \frac{\vec{J}\cdot\vec{E}}{\left(\rho C_p\right)_{nf}},\ \left[q_r = -\frac{\partial T^4}{\partial y}\frac{4\sigma_e}{3\beta_R},\ T^4 \cong 4T_c^3T - 3T_c^4\right]', \\ \nabla\cdot\vec{J} = -\frac{\partial q}{\partial t}, -\nabla\varphi = \vec{E}, q - \nabla\cdot\varepsilon\vec{E} = 0, \end{cases} \tag{5}$$

μ_{nf}, $\left(\rho C_p\right)_{nf}$ and ρ_{nf} are (Sheikholeslami and Bhatti 2017):

$$\begin{aligned} \mu &= A_1 + A_2(\Delta\varphi) + A_3(\Delta\varphi)^2 + A_4(\Delta\varphi)^3, \\ (\rho C_p)_{nf} &= \phi(\rho C_p)_s + (1-\phi)(\rho C_p)_f, \\ \rho_{nf} &= \rho_f(1-\phi) + \rho_s\phi, \end{aligned} \tag{6}$$

k_{nf} can estimated as:

$$\frac{k_{nf}}{k_f} = \frac{(m+1)k_f + \phi(k_p - k_f)m + k_p - \phi(k_f - k_p)}{k_p + mk_f - (k_p - k_f)\phi + k_f}. \tag{7}$$

Related parameters are illustrated in Tables 1, 2 and 3

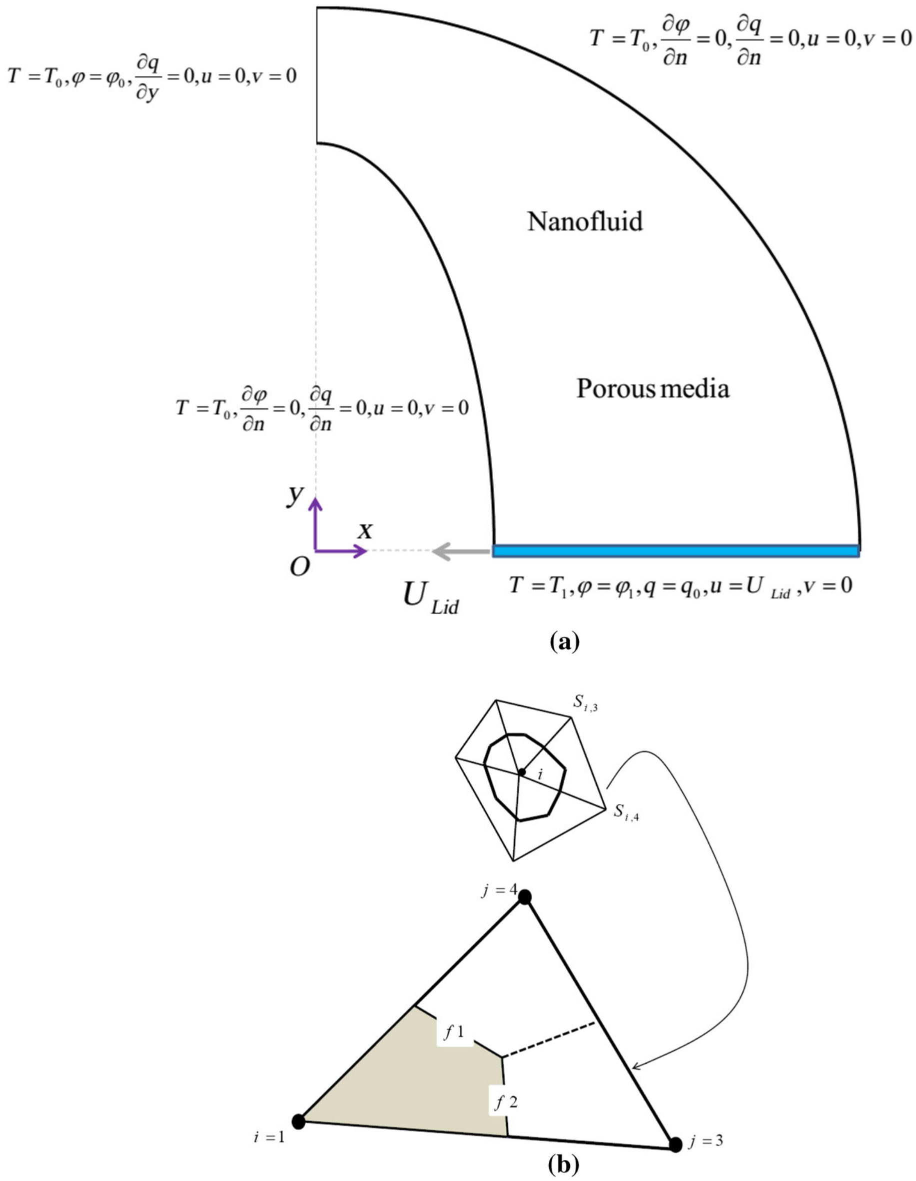


Fig. 1 **a** Geometry and the boundary conditions with; **b** a sample triangular element and its corresponding control volume

Final forms of equations are:

$$\begin{cases} \nabla \cdot \vec{V} = 0, \\ \dfrac{S_E}{\rho_{nf}/\rho_f} q\vec{E} + \dfrac{1}{\mathrm{Re}} \dfrac{\rho_{nf}/\rho_f}{\mu_{nf}/\mu_f} \nabla^2 \vec{V} - \nabla p - \dfrac{1}{\mathrm{Re}\, Da} \dfrac{\mu_{nf}}{\mu_f} \left(\dfrac{\rho_{nf}}{\rho_f} \right)^{-1} \vec{V} = \left((\vec{V} \cdot \nabla)\vec{V} + \dfrac{\partial \vec{V}}{\partial t} \right) \\ \left((\vec{V} \cdot \nabla)\theta + \dfrac{\partial \theta}{\partial t} \right) = \left(k_{nf}/k_f \right) \dfrac{1}{Pr\mathrm{Re}} \left((\rho C_p)_{nf}/(\rho C_p)_f \right)^{-1} \nabla^2 \theta + Ec(\vec{J} \cdot \vec{E})\, S_E \dfrac{(\rho C_p)_f}{(\rho C_p)_{nf}} + \dfrac{4}{3} \left(\dfrac{k_{nf}}{k_f} \right)^{-1} Rd \dfrac{\partial^2 \theta}{\partial Y^2} \\ \vec{E} + \nabla \varphi = 0, \nabla \cdot \vec{J} + \dfrac{\partial q}{\partial t} = 0, q = \nabla \cdot \varepsilon \vec{E}, \end{cases} \tag{8}$$

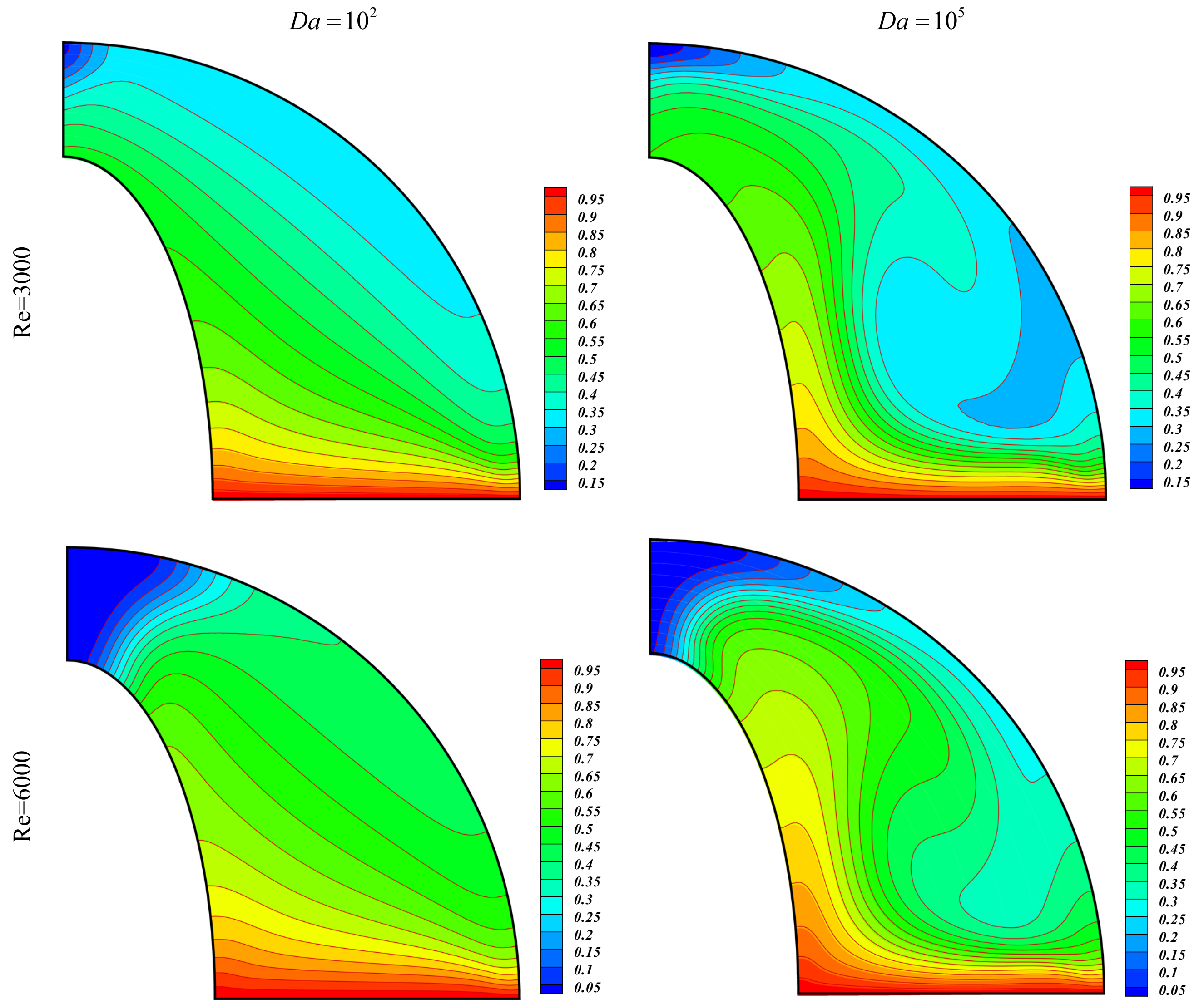


Fig. 2 Electric density distribution injected by the bottom electrode when $\Delta\varphi = 10$ kV, $\phi = 0.05, Rd = 0.8$

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

$$(\bar{u}, \bar{v}) = \frac{(u, v)}{U_{Lid}}, \overline{\varphi} = \frac{\varphi - \varphi_0}{\nabla\varphi}, \theta = \frac{T - T_0}{\nabla T},$$
$$\bar{p} = \frac{P}{\rho U_{Lid}^2} \bar{q} = \frac{q}{q_0}, \bar{E} = \frac{E}{E_0}, \bar{t} = \frac{tU_{Lid}}{L}, \tag{9}$$
$$\nabla T = T_1 - T_0, \nabla\varphi = \varphi_1 - \varphi_0, (\bar{y}, \bar{x}) = \frac{(y, x)}{L},$$

Stream function and vorticity must be considered:

Table 2 The coefficient values of 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

$$\Psi = \frac{\psi L}{U_{Lid}}, v = -\frac{\partial\psi}{\partial x}, \Omega = \frac{\omega}{LU_{Lid}}, \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \frac{\partial\psi}{\partial y} = u, \tag{10}$$

Nu_{loc} and Nu_{ave} are:

Table 3 The values of shape factor of different shapes of nanoparticles

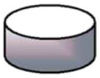
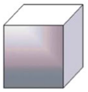
m	Spherical		3
	Platelet		5.7
	Cylinder		4.8
	Brick		3.7

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

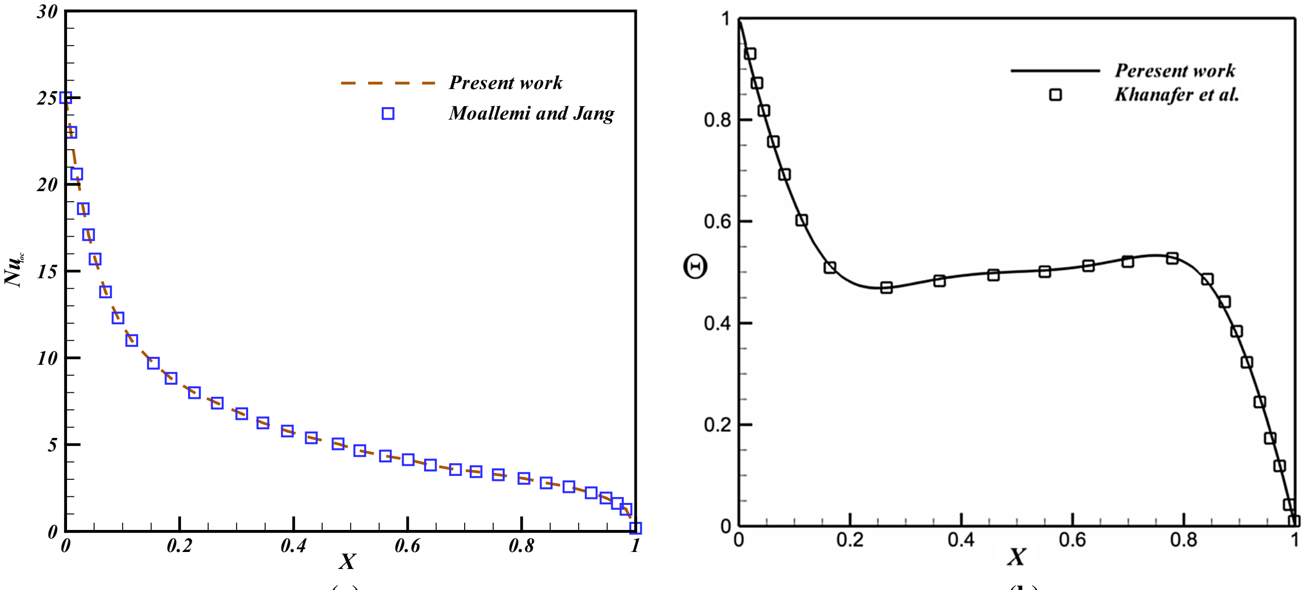
51 × 151	61 × 181	71 × 211	81 × 241	91 × 271	101 × 301
7.44512	7.45338	7.45965	7.46148	7.46229	7.46404

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

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

3.2 Macroscopic approach

Sheikholeslami (2018) was the first researcher who utilized CVFEM for heat transfer problems. This approach has been generated by combining FEM and FVM with triangular element. In this FORTRAN code, Gauss–Seidel method was used in last step.



(a)

(b)

Fig. 3 **a** Comparison of the local Nusselt number over the lid wall between the present results and Moallemi and Jang (1992) at Re = 500, Ri = 0.4, and Pr = 1; **b** Comparison of average Nusselt number between the present results and numerical results by Khanafer et al. (2003) $Gr = 10^4$, $\phi = 0.1$ and $\Pr = 6.8(Cu - water)$

4 Mesh study and code validation

Altering mesh size must not change the results. Thus, various grids should be checked. As illustrated in Table 4, a mesh size of 81 × 241 must be suggested. Figure 3 displays verification of written code (Moallemi and Jang 1992; Khanafer et al. 2003).

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

	Da	
	10^2	10^5
Spherical	3.2975	7.194161
Brick	3.33883	7.268677
Cylinder	3.400007	7.378166
Platelet	3.446857	7.461483

5 Results and discussion

In current paper, fluid transportation in existence of Coulomb forces is displayed. The permeable cavity is full of Fe_3O_4–$C_2H_6O_2$. Roles of supplied voltage ($\Delta\varphi =$ 0–10 kV), Darcy number ($Da = 10^2$–10^5), Reynolds number (Re = 3000–6000), Radiation ($Rd =$ 0–0.8), nanoparticle concentration ($\phi =$ 0–5%) are depicted graphically.

Platelet shape is the best shape in view of heat transfer as displayed in Table 5. Due to this fact, other results are presented for this shape. Impacts of Re, Da and $\Delta\varphi$ on streamlines and isotherm were displayed in Figs. 4, 5, 6

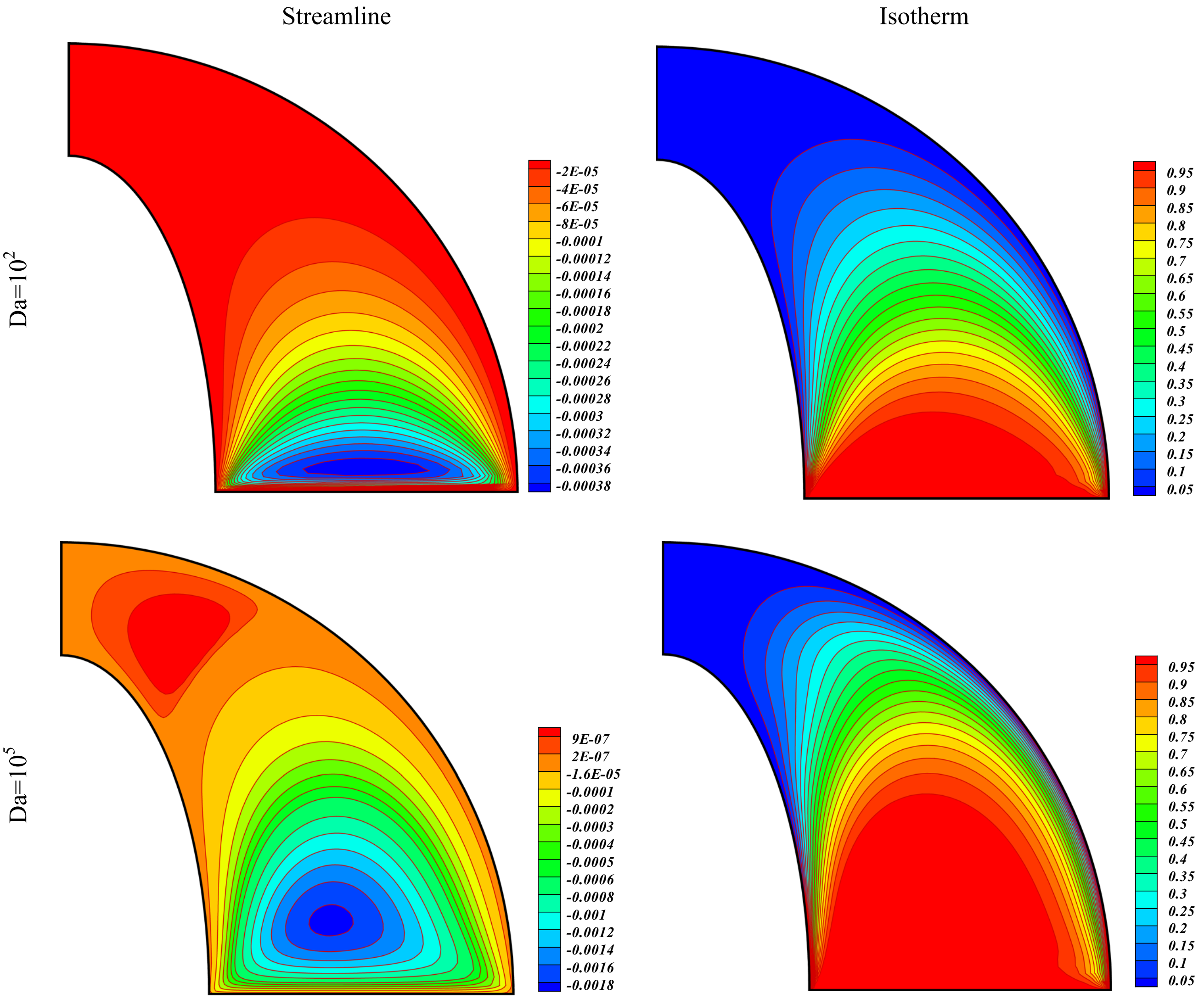


Fig. 4 Effect of Darcy number on streamlines and isotherm when $\mathrm{Re} = 3000, \Delta\varphi = 0kV, \phi = 0.05, Rd = 0.8$

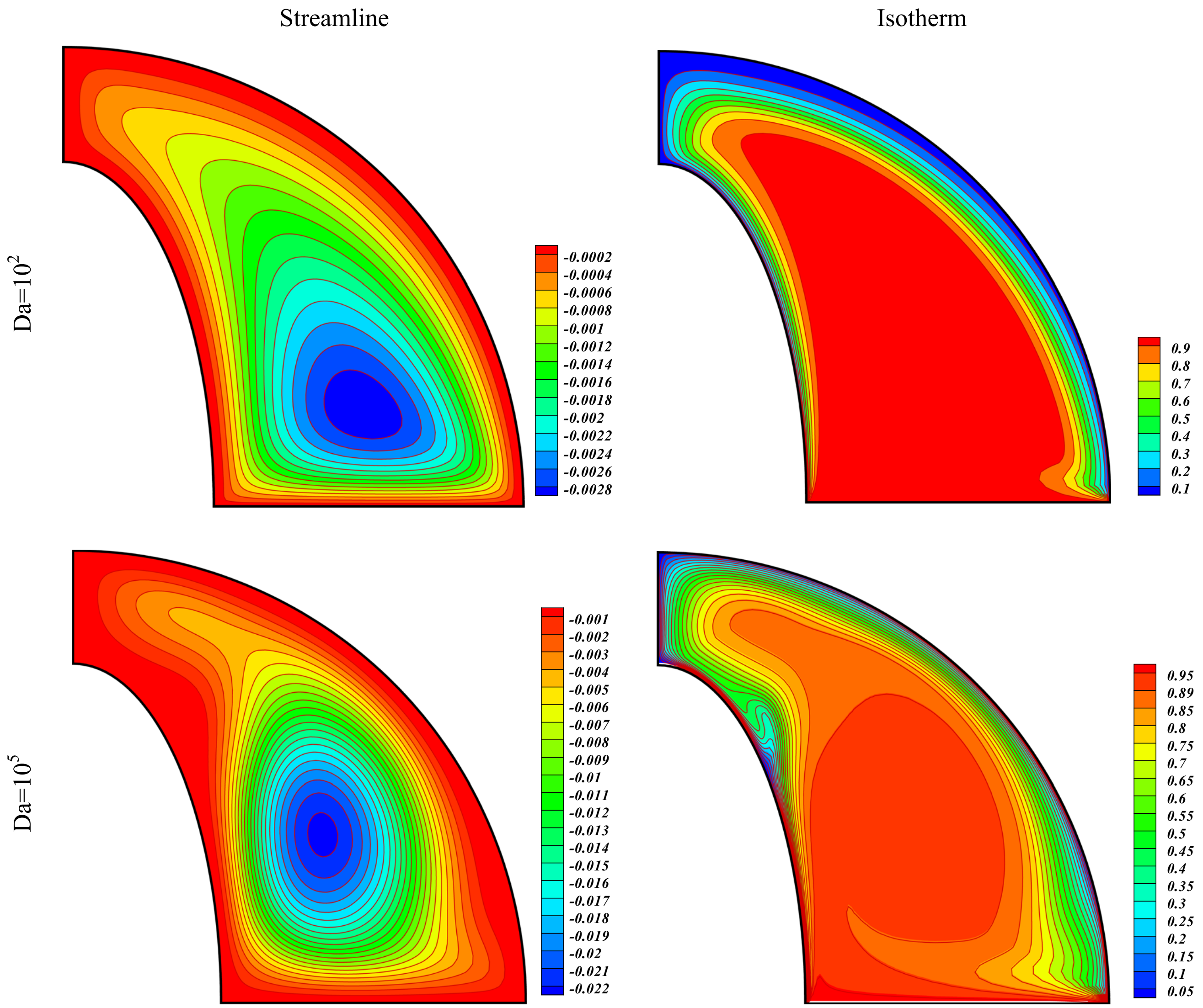


Fig. 5 Effect of Darcy number on streamlines and isotherm when $\mathrm{Re} = 3000, \Delta\varphi = 10\ \mathrm{kV}, \phi = 0.05, Rd = 0.8$

and 7. When lid velocity is low, there is one rotating vortex. As Darcy number augments, $|\Psi_{\max}|$ enhances and main vortex goes upward. Existence of electric force leads the primary vortex to be stronger. Isotherms have complex shape in presence of Coulomb forces. As lid velocity enhances, thermal plume generates. As Coulomb force increases, the strength of primary vortex enhances and stronger thermal plume generates.

Nu_{ave} variation respect to active parameters is shown in Fig. 8. Below formula can be extracted:

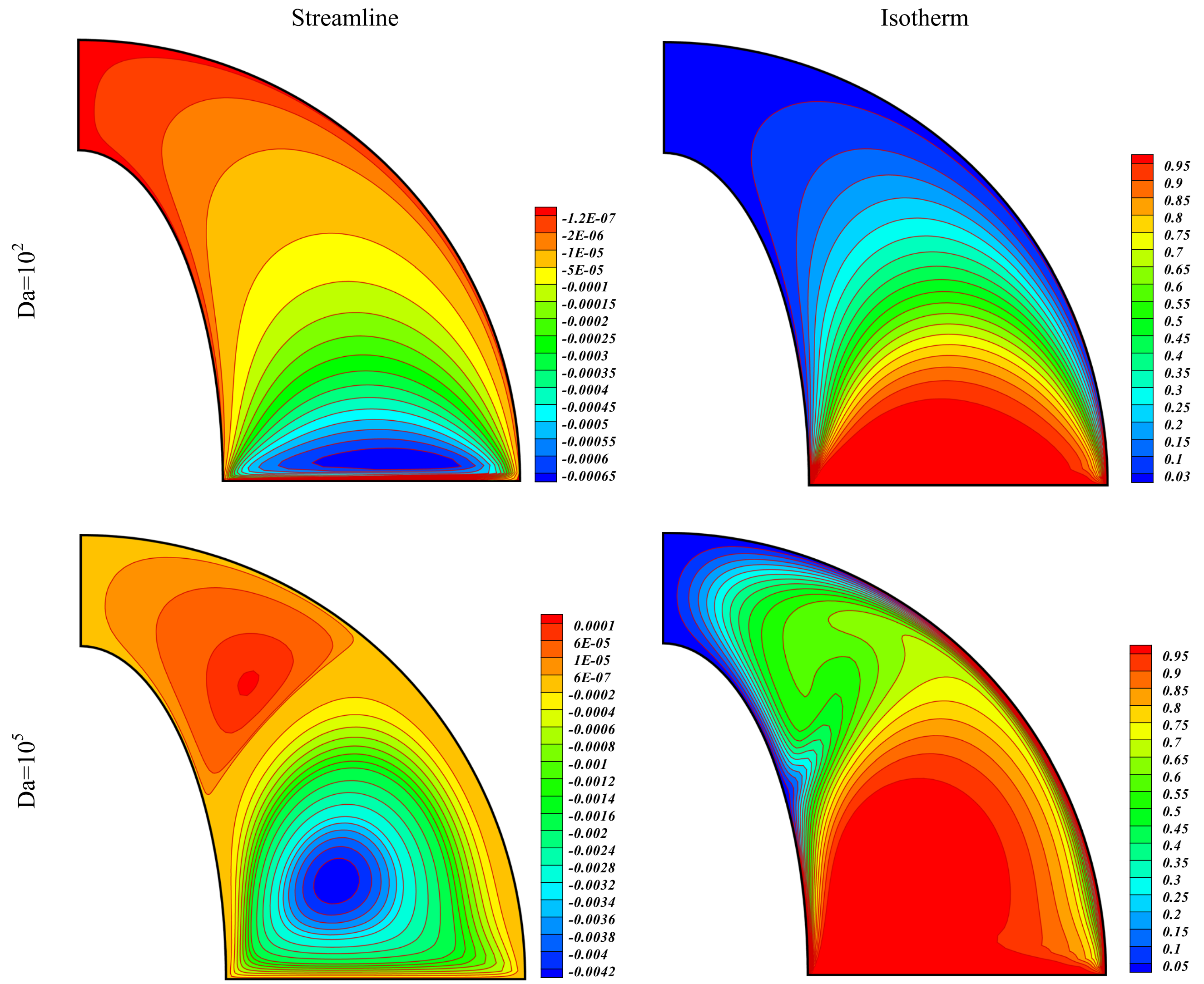


Fig. 6 Effect of Darcy number on streamlines and isotherm when $\mathrm{Re} = 6000, \Delta\varphi = 0\ \mathrm{kV}, \phi = 0.05, Rd = 0.8$

$$\begin{aligned} Nu_{ave} = & -3.48 + 0.1\Delta\varphi + 2.1\mathrm{Re}^* + 0.12\Delta\varphi\log(Da) \\ & + 0.36\log(Da) + 2.6Rd - 0.13\Delta\varphi\mathrm{Re}^* \\ & - 0.11\log(Da)\mathrm{Re}^* - 1.18\mathrm{Re}^*Rd \\ & + 1.06\log(Da)Rd + 0.33Rd\Delta\varphi + 0.034\Delta\varphi^2 \\ & - 0.015(\log(Da))^2 + 1.03Rd^2 - 0.15(\mathrm{Re}^*)^2, \end{aligned} \tag{13}$$

where $\mathrm{Re}^* = 0.001\mathrm{Re}$. When SE is not zero, Nu reduces with augment of Re. Electric field makes convection to augment. Convection increases with augment of Rd, Da.

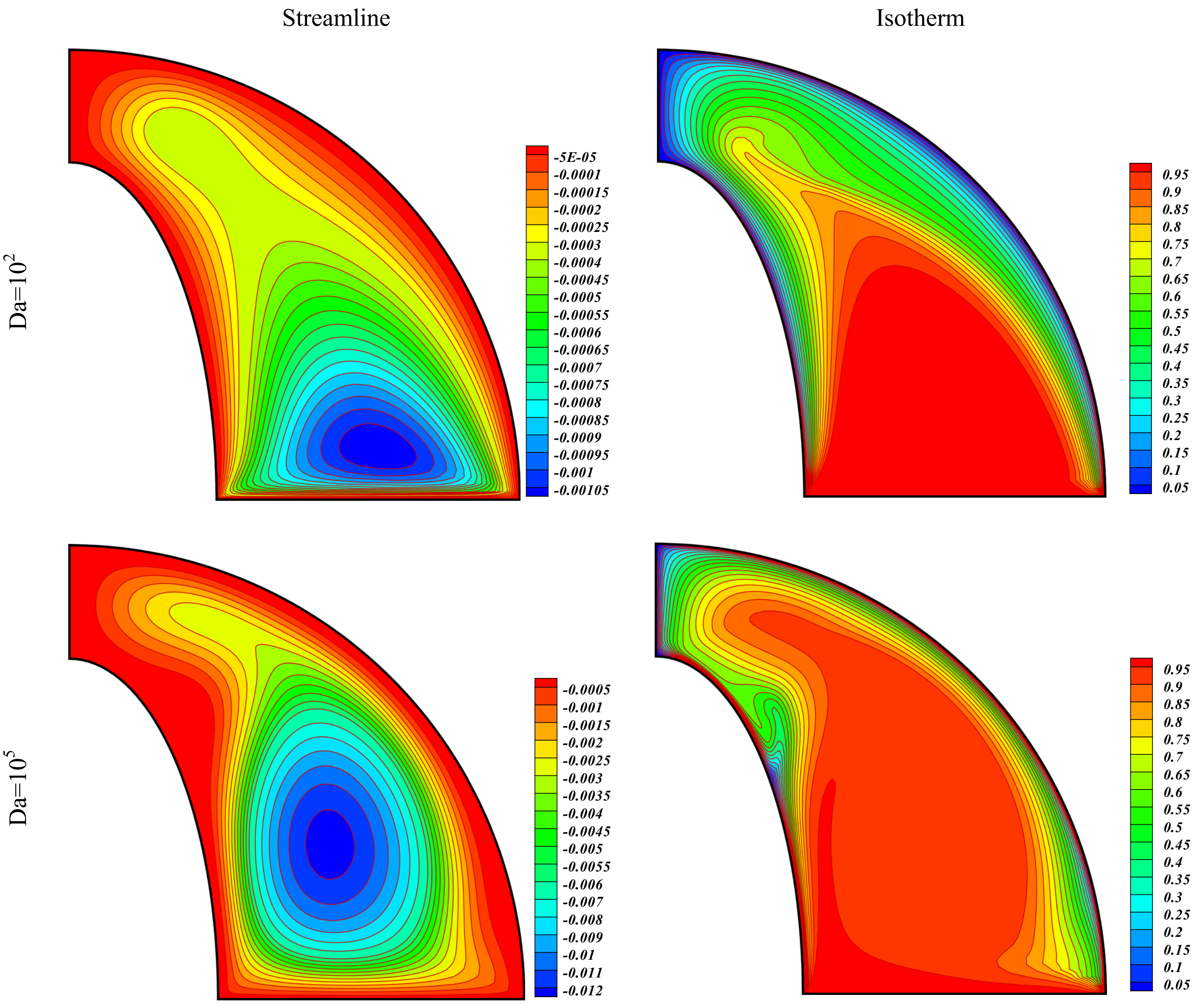
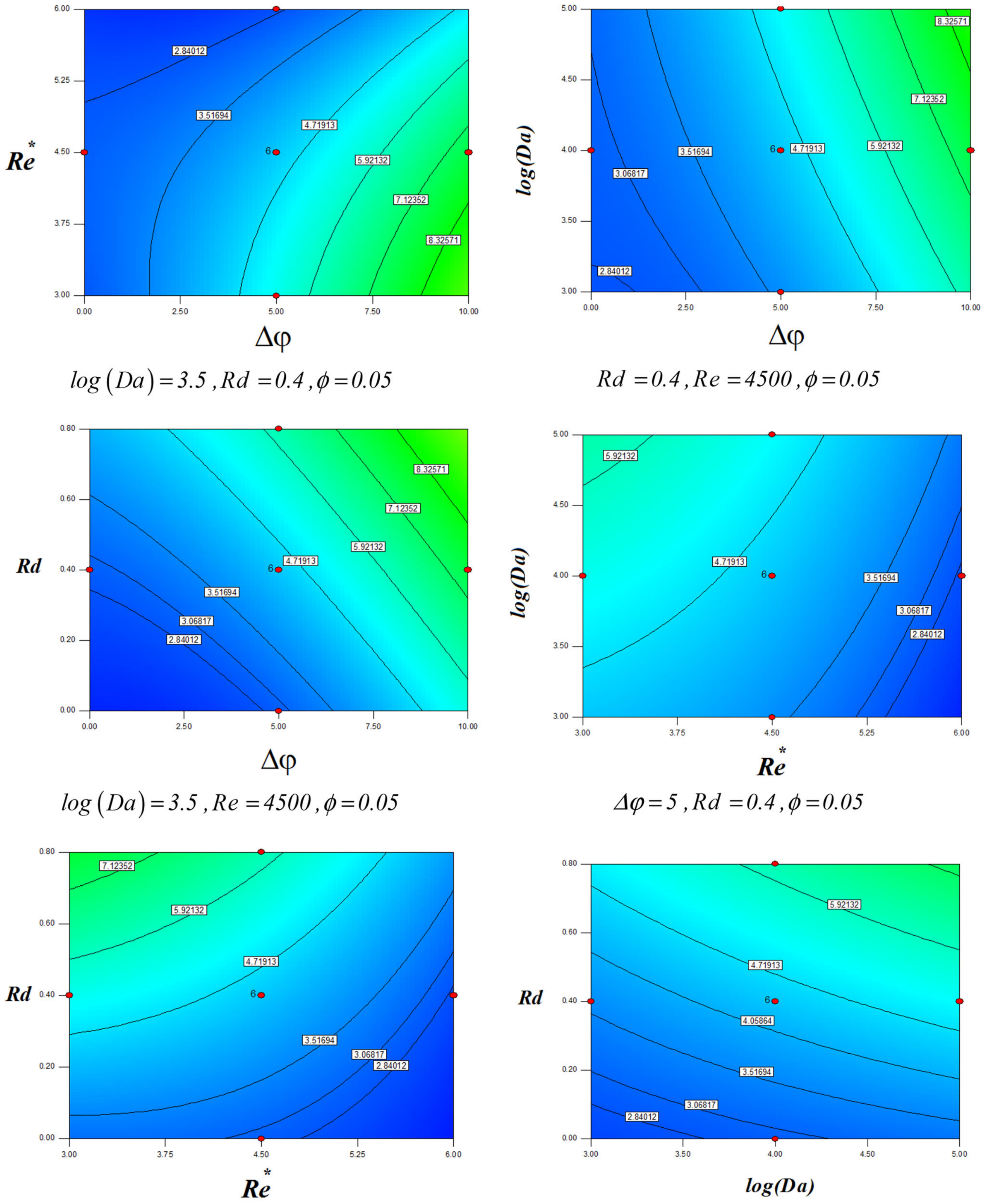


Fig. 7 Effect of Darcy number on streamlines and isotherm when $\mathrm{Re} = 6000, \Delta\varphi = 10\ \mathrm{kV}, \phi = 0.05, Rd = 0.8$



$\log(Da) = 3.5, Rd = 0.4, \phi = 0.05$

$Rd = 0.4, Re = 4500, \phi = 0.05$

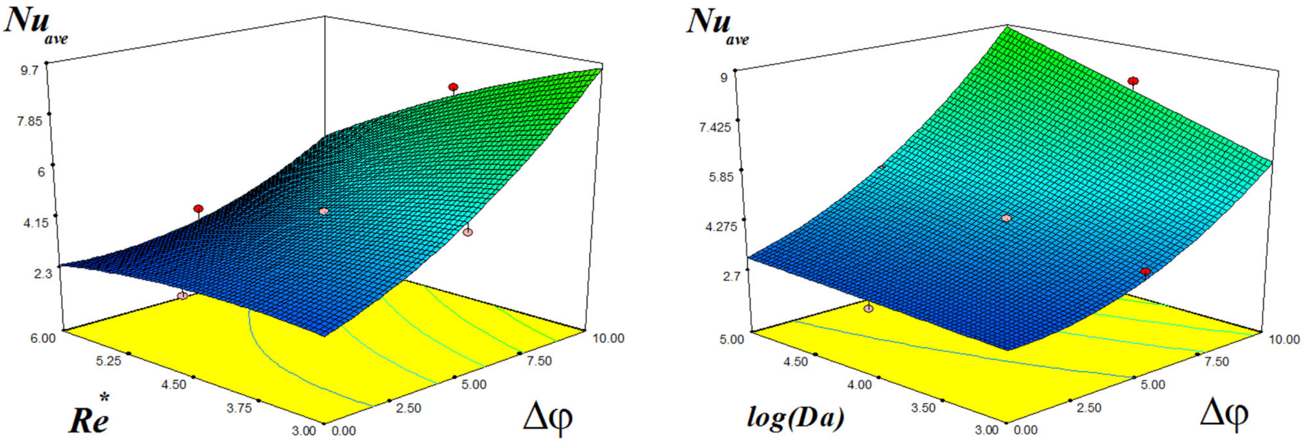
$\log(Da) = 3.5, Re = 4500, \phi = 0.05$

$\Delta\varphi = 5, Rd = 0.4, \phi = 0.05$

$\log(Da) = 3.5, \Delta\varphi = 5, \phi = 0.05$

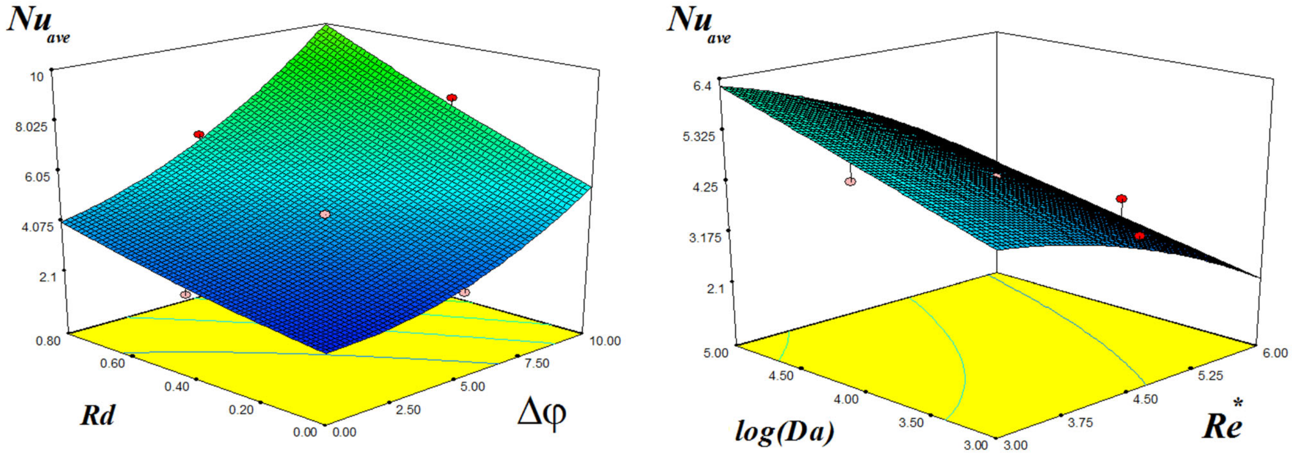
$\Delta\varphi = 5, Re = 4500, \phi = 0.05$

Fig. 8 Effects of Da, $\Delta\varphi$, Rd and Re on average Nusselt number



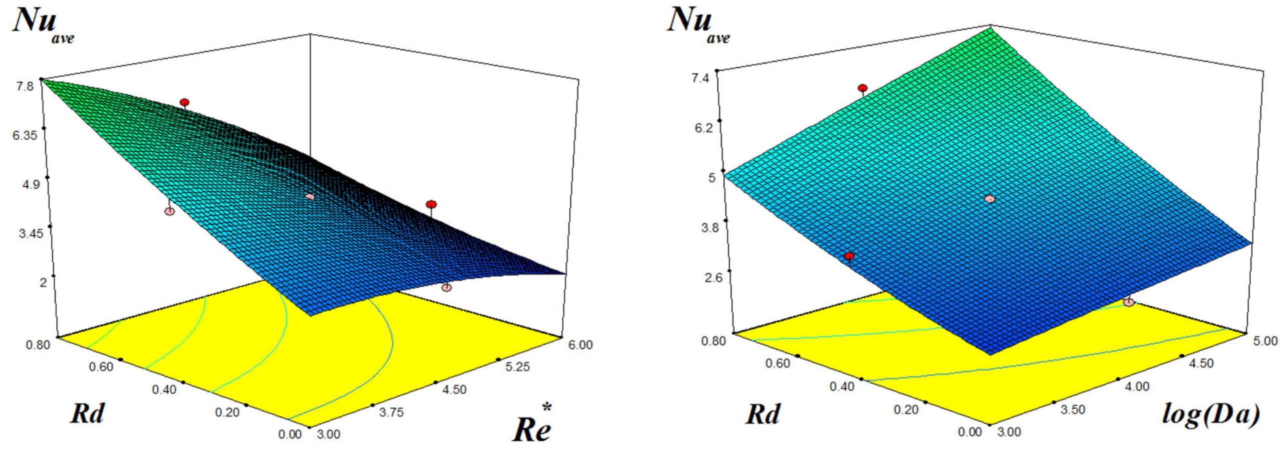
$log(Da) = 3.5, Rd = 0.4, \phi = 0.05$

$Rd = 0.4, Re = 4500, \phi = 0.05$



$log(Da) = 3.5, Re = 4500, \phi = 0.05$

$\Delta\varphi = 5, Rd = 0.4, \phi = 0.05$



$log(Da) = 3.5, \Delta\varphi = 5, \phi = 0.05$

$\Delta\varphi = 5, Re = 4500, \phi = 0.05$

Fig. 8 continued

6 Conclusions

In this attempt, nanoparticles transportation due to radiation and forced convection with supplied voltage is simulated. A new numerical comparison indicates the correctness of present technique. Contours were illustrated for various variables. Results display that Coulomb forces makes to generate thermal plume. Convection rises with considering radiation.

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