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Investigation of thermal treatment of hybrid nanoparticles in a domain with different permeabilities

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Abstract

Porous domain filled with nanoliquid was scrutinized in the current article. Magnetic force and permeability were considered as main effective variables, and their influences were involved in momentum. Also, energy equation has a source term related to radiation. Outputs were achieved with CVFEM simulation. As permeability augments, forces against the flow decline. So, stronger eddy appears and temperature gradient augments. Structure of fluid gets affected more significantly by Ha when permeability increases. Nu increases by increments of Da related to greater velocity of nanomaterial, and similar tendency for Nu has been reported with rise of Ra. With intensification of Ha, Nu reduces because of lower distortion of isotherms. The adverse impact of Lorentz force reduces when radiation impact is neglected.

Keywords Radiation · Nanoliquid · Lorentz · Porous space · Numerical

Introduction

Unique features and wonderful heat transfer capability of nanomaterial are because of small size and sizable surface space. Nanomaterials as a suspended part into base liquid modify its thermal and physical characteristics [1–7]. Nanofluids demonstrated as a surplus to novel thermal transfer medium. The colloidal combination of nanoparticles that were suspended in base liquid indicated better heat performance rather than pure fluids [8–15]. A numerical investigation was carried out by Purusothaman et al. [16] to consideration of 3D normal convection in cooler in a way that isothermal heaters with 3 × 3 array were put on one of vertical walls in the enclosure filled by nanofluid. Results revealed that cooling performance reached the highest rate by Cu–H_2O nanofluid in comparison with AL_2O_3–H_2O one. In addition to, the volume concentration of solid nanoparticles and Rayleigh number increased by the increment of normal Nusselt number. Babazadeh et al. [17] examined the role of imposition of MHD on nanopowder migration through a domain contains two sheets. They assumed that homogeneous fluids exist in domain and plates can move vertically. Researchers have conducted many researches on nanofluids [18–28] and tried to show the effective role of carrier fluid. Aly [29] considered the circular chambers in a porous channel with full of nanofluid to study of thermodiffusion behavior on free convection. Studies showed that the establishment and size of cells in the enclosure are considerably controlled by Darcy parameter, Rayleigh number, positions and sizes of the internal circular cylinders. Moreover, there was well agreement between the numerical outcomes and experimental tests.

Hussein and his friends [30] studied the flow of natural convection under the situation of hydrodynamic-magneto in the curved T formed chamber with the presence of

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nanofluids with various nanoparticles dimension. They indicated that Nu_{ave} went up when the tilted angle, Ra, heat source position and nanoparticles fraction concentration increased. However, the increase in Hartmann number and length of heat source led to a decrease in average Nusselt number. Scientists have done numerous studies on numerical approaches [31–42], and this work helps them to reduce the experimental cost. Abdallaoui and colleagues [43] considered a chamber with the shape of isosceles triangle which was located in a quadrangular enclosure with full of water–silver nanofluid and studied the characteristics of free convection using LBM. They changed silver's volume concentration in range between 0 and 0.1 and location of heated triangular chamber vertically. As a consequence, the amount of stream performance was influenced considerably by the heated block position as well as volume fraction of nanoparticles. Evidently, the nanoparticles existence improves the flow momentum and hence convection rate. A simulation was carried out by Boualit et al. [44] to investigation of the rate of free convection in a chamber while filled with nanomaterial. As a result, nanoparticles diameter was effective on thermal transfer solely when thermal scattering was considerable. In order to quantify the thermal transfer severity with regard to particle diameter, concentration and Rayleigh number, a relation with 99.94% confidence coefficient was presented. Numerous researches have been conducted by researchers about thermal units [45–55], and they focus on achieving the best design. A simulation research has been scrutinized by Kahwaji et al. [56] to evaluation of heat transfer of square chamber which was mounted in a conduit full of $CuO–H_2O$. As a result, gradual augment in normal Nu with enhancement in the concentration of powders was observed.

3D normal convective thermoregulation of heaters with the type of quad flat non-lead (QFN) that were put in porous chamber, leaked by $H_2O–Cu$ nanofluid, was examined mathematically by Purusothaman [57]. The results revealed that the nanofluid impact from total Nu grew with augment of Darcy. However, the impact decreased with growth of Ha. The total Nu obtained its highest amount in chamber side aspect ratio between 3 and 1.5 with regard to Da. Sheremet and his colleagues [58] analytically studied a porous horizontal tubular ring that filled by nanofluid and specified its stream performance at various Rayleigh number. It is shown that addition of nanomaterial into the net H_2O altered the flow behavior at low Ra. Various analyses have been presented by designers in thermal units [59–69] in recent decade. Vijaybabu and his friends [70] carried out examination on heat transfer properties and flow of a penetrable chamber with the shape of triangle which put in a channel which was full of $H_2O–Al_2O_3$ nanofluid. They found that the nanofluid volume fraction had control of heat or friction irreversibility. Da enhancement increased the heat transportation, while it decreased the temperature monotony.

In the current investigation, convective treatment of nanoliquid with involving Lorentz force was performed. Porous medium was involved, and to insert its impact on equations, non-Darcy law was applied. With considering homogeneous nanoliquid and adding radiation term, final equations can be achieved and to solve them, CVFEM was selected. The main outputs are contours and innovative formula for Nu.

Formulation of problem

The current simulation domain consists of one circular cold and one square hot cylinder. Permeable zone was full of nanoliquid which was produced by hybrid nanopowders and water [1], and features of new fluid were obtained by homogenous approach [1]. In momentum equations, Lorentz, buoyancy and permeability impacts were imposed and energy equation has extra source due to radiation modeling. As it can be observed from Fig. 1, enclosure has symmetric boundary condition which allows us to present just half of it in contours. No slip condition and impermeable walls were other assumptions and PDEs can be introduced as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

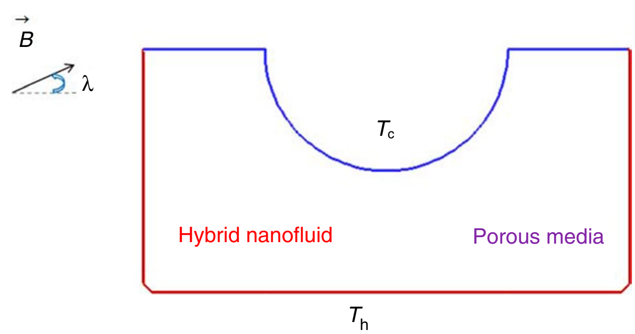

Fig. 1 Geometry of this article filled with hybrid nanomaterial

$$\left(\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial x^2}\right)\mu_{\mathrm{nf}}-\frac{1}{K}u\mu_{\mathrm{nf}}-\frac{\partial P}{\partial x} = \left(v\frac{\partial u}{\partial y}+u\frac{\partial u}{\partial x}\right)\rho_{\mathrm{nf}} \tag{2}$$

$$\frac{\mu_{\mathrm{nf}}}{\rho_{\mathrm{nf}}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\left(T_{\mathrm{c}}-T\right)g\beta_{\mathrm{nf}}-\frac{\partial P}{\partial y}\frac{1}{\rho_{\mathrm{nf}}} -\frac{1}{\rho_{\mathrm{nf}}}\frac{\mu_{\mathrm{nf}}}{K}v+\sigma_{\mathrm{nf}}B_0^2[-v]=u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y} \tag{3}$$

$$\frac{\partial q_{\mathrm{r}}}{\partial y}\left(C_{\mathrm{p}}\rho\right)_{\mathrm{nf}}^{-1}+\left(\frac{\partial T}{\partial y}v+\frac{\partial T}{\partial x}u\right)=k_{\mathrm{nf}}\left(\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial x^2}\right)\left(C_{\mathrm{p}}\rho\right)_{\mathrm{nf}}^{-1}, \left[T^4\cong 4T_{\mathrm{c}}^3T-3T_{\mathrm{c}}^4, q_{\mathrm{r}}=-\frac{4\sigma_{\mathrm{e}}}{3\beta_{\mathrm{R}}}\frac{\partial T^4}{\partial y}\right] \tag{4}$$

Nanoliquid which was utilized in the current article has features same as material mentioned in [1]. Two-phase approach needs greater computational cost, and we did not use such model and prefer to employ single-phase method with involving experimental formulas in prediction of features [1].

It is better to reduce number of scalars and for this fact; we tried to omit ∇p with considering vorticity definition.

$$\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}=-\omega, \frac{\partial \psi}{\partial y}=u, \frac{\partial \psi}{\partial x}=-v \tag{5}$$

Definition of parameters was as follows:

$$V=\frac{vL}{\alpha_{\mathrm{nf}}}, U=\frac{uL}{\alpha_{\mathrm{nf}}}, \Delta T=\frac{q''L}{k_{\mathrm{f}}}, \Omega=\frac{\omega L^2}{\alpha_{\mathrm{nf}}}, (X,Y)=\frac{(x,y)}{L}, \Psi=\frac{\psi}{\alpha_{\mathrm{nf}}}, \theta=\frac{T-T_{\mathrm{c}}}{\Delta T}, \tag{6}$$

Based on above, the last form of equations is:

$$\frac{\partial^2\Psi}{\partial Y^2}+\frac{\partial^2\Psi}{\partial X^2}=-\Omega, \tag{7}$$

$$V\frac{\partial\Omega}{\partial Y}+U\frac{\partial\Omega}{\partial X}=\Pr\frac{A_5}{A_1}\frac{A_2}{A_4}\left(\frac{\partial^2\Omega}{\partial Y^2}+\frac{\partial^2\Omega}{\partial X^2}\right) +\Pr\ \mathrm{Ha}^2\frac{A_6}{A_1}\frac{A_2}{A_4}\left(-\frac{\partial V}{\partial X}\right) +\Pr\ \mathrm{Ra}\frac{A_3A_2^2}{A_1A_4^2}\left(\frac{\partial\theta}{\partial X}\right)-\frac{A_2}{A_4 Da}A_5\Omega\frac{\Pr}{A_1}, \tag{8}$$

$$\left(1+\frac{4}{3}\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}\right)^{-1}\mathrm{Rd}\right)\frac{\partial^2\theta}{\partial Y^2}=\frac{\partial\theta}{\partial X}\frac{\partial\Psi}{\partial Y}-\frac{\partial\Psi}{\partial X}\frac{\partial\theta}{\partial Y}-\left(\frac{\partial^2\theta}{\partial X^2}\right) \tag{9}$$

$$\mathrm{Ha}=B_0L\left(\mu_{\mathrm{f}}/\sigma_{\mathrm{f}}\right)^{-0.5}, \mathrm{Ra}=g(\rho\beta)_{\mathrm{f}}\Delta TL^3/\left(\alpha_{\mathrm{f}}\mu_{\mathrm{f}}\right), \Pr=\upsilon_{\mathrm{f}}/\alpha_{\mathrm{f}}, A_1=\frac{\rho_{\mathrm{nf}}}{\rho_{\mathrm{f}}}, A_2=\frac{\left(\rho C_{\mathrm{p}}\right)_{\mathrm{nf}}}{\left(\rho C_{\mathrm{p}}\right)_{\mathrm{f}}}, A_3=\frac{(\rho\beta)_{\mathrm{nf}}}{(\rho\beta)_{\mathrm{f}}}, A_4=\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}, A_5=\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{f}}}, A_6=\frac{\sigma_{\mathrm{nf}}}{\sigma_{\mathrm{f}}} \tag{10}$$

To evaluate Nu, the following formulas can be implemented:

$$\mathrm{Nu}_{\mathrm{loc}}=\frac{\partial\theta}{\partial n}\left(1+\frac{4}{3}\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}\right)^{-1}\mathrm{Rd}\right)\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{f}}}\right) \tag{11}$$

$$\mathrm{Nu}_{\mathrm{ave}}=\frac{1}{S}\int_0^s \mathrm{Nu}_{\mathrm{loc}}\,\mathrm{d}s \tag{12}$$

The current 2D geometry was modeled by means of CVFEM. Final equations do not have ∇p, and such steady formulations were simulated with this approach which was basically belong to Sheikholeslami [55]. He applied such approach for various problems (thermal units). Triangular gird of this method boosts us to consider complex geometry, and Table 1 is illustrated to depict the sensitivity of grid.

Results and discussion

In current attempts, geometry with one upper cold was scrutinized which is full of hybrid nanomaterial and buoyancy force due to existence of below hot wall affects the behavior of carrier fluid and create circulation. In outputs, the half of domain was demonstrated because it is symmetric. For controlling the migration of nanopowders, horizontal magnetic field was added externally which produces constant Lorentz forces and its impacts were added in momentum equations. Besides, radiation term based on Rosseland approach was

Table 1 $\mathrm{Nu}_{\mathrm{ave}}$ with alteration of grid size at $\mathrm{Ra}=10^5$, $\mathrm{Rd}=0.8$, $\mathrm{Da}=100$, $\mathrm{Ha}=60$ and $\phi=0.003$

61×181	51×151	81×241	71×211	91×271
18.2307	18.2285	18.2322	18.2314	18.2358

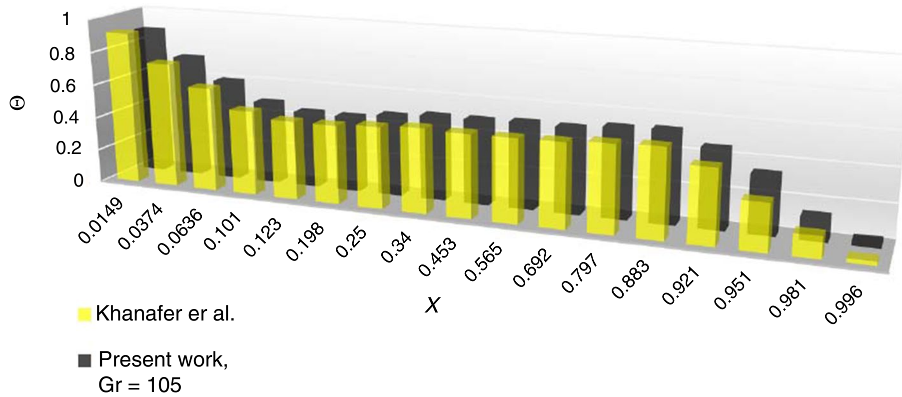

Fig. 2 Verification of temperature profile with old article [71]

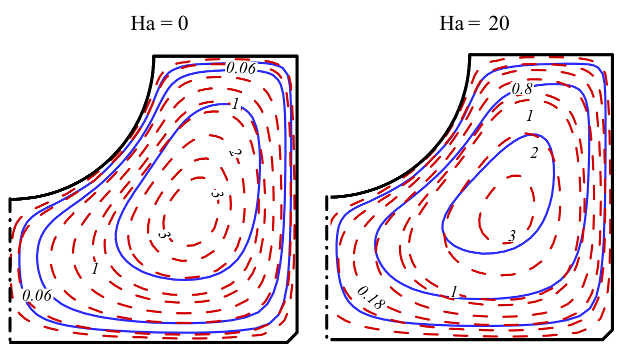

Fig. 3 Ψ variation with rise of Da (Da = 100 (—) and Da = 0.01 (---)) in two cases at Ra = 10^3, Rd = 0.8

involved and CVFEM was imposed for solving equations. For the aim of testing accuracy of simulation, square domain filled with nanomaterial was considered same as [71], and outcomes are demonstrated in Fig. 2 and indicates nice concordance. In rest outputs, contours and new formula for Nu were presented.

Variations of Ψ with changing permeability when Ha = 0 and Ha = 20 are illustrated in Fig. 3. To change the permeability of region, Da can be changed in modeling. Greater Da means faster speed of nanomaterial and stronger power of vortex. Additionally, this graph proves that augmenting Ha makes the impact of Da to become weaker. Flow structure is noticed to be function of both Da and Ha. Structures of flow and temperature distribution are illustrated in Figs. 4 and 5. When Ra = 10^5, Da = 0.01, two rotating circulations have been generated, of which the lower one is weaker. They rotate in reverse direction of each other. Generating such vortexes helps to produce thermal plume which enforces the isotherm become denser close to hot wall. As Ha grows, the vortexes become weaker and direction of affecting thermal plume changes. It means that ∇T near the bottom wall becomes more than right wall. As Da increases to 100, two vortexes convert to one counter clockwise stronger vortex and thermal plume over a circular wall disappears. Due to shape of inner surface, new vortex stretches along its surface and imposition of Ha guides to lower values of Ψ and center of vortex shifts downward. Distortion of isotherm declines with growth of Ha. In case of Da = 100, thermal plume over the cold surface shifts to vertical symmetric line and makes the isotherms denser near this region. One main aim of design of thermal unit is the highest Nu. Thus, based on simulation data, we performed new formula for this function.

$$\begin{aligned} Nu_{ave} = {} & 8.98 + 4.77Rd + 0.46Da^* - 0.53Ha^* \\ & - 0.36Ha^* \log(Ra) + 0.29Da^*Rd \\ & + 0.36\log(Ra)\, Da^* - 0.31Rd\, Ha^* \\ & - 0.2Da^*\, Ha^* + 4.73\log(Ra) \end{aligned} \tag{13}$$

In this formula, not only Da and Ha but also Ra and Rd have been considered as variables. Augmentation of Nu with intensification of Da is due to easier movement of nanomaterial. Growth of Ha creates stronger resistance for nanomaterial flow and velocity declines and thinker boundary layer leads to lower Nu. As buoyancy forces elevate, the distortion of isotherm intensifies and higher Nu can be achieved. Formulation of Nu shows direct relation of Nu with Rd, and

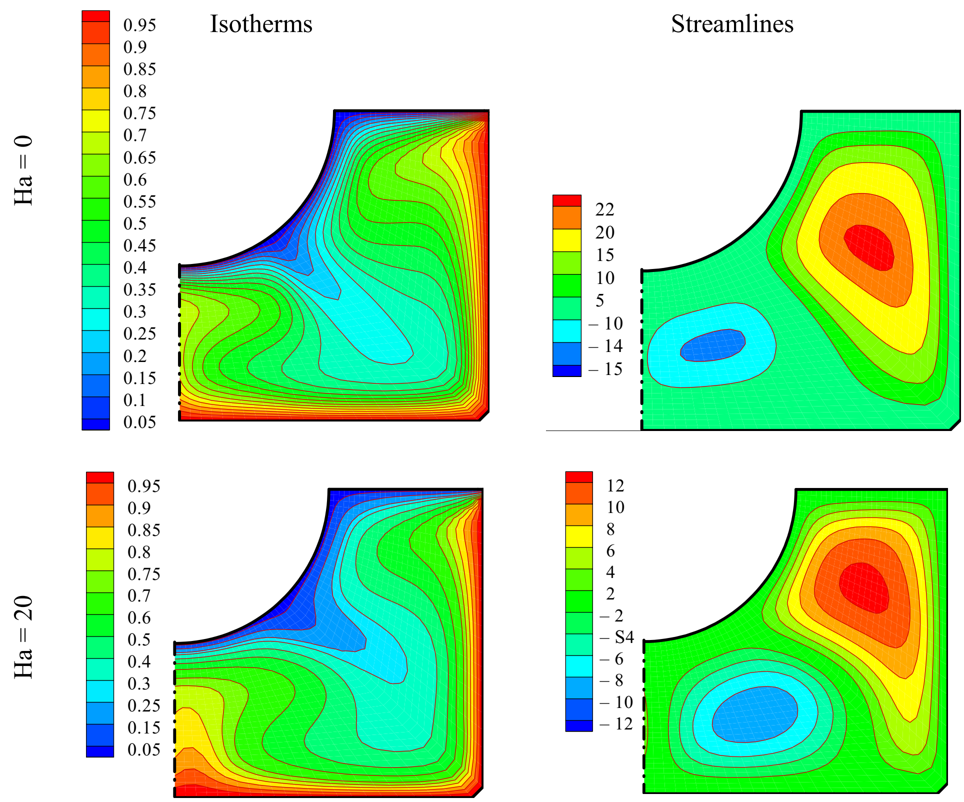

Fig. 4 Thermal and hydraulic behavior with the values of Ha at $Ra = 10^5,\ Da = 0.01,\ Rd = 0.8$

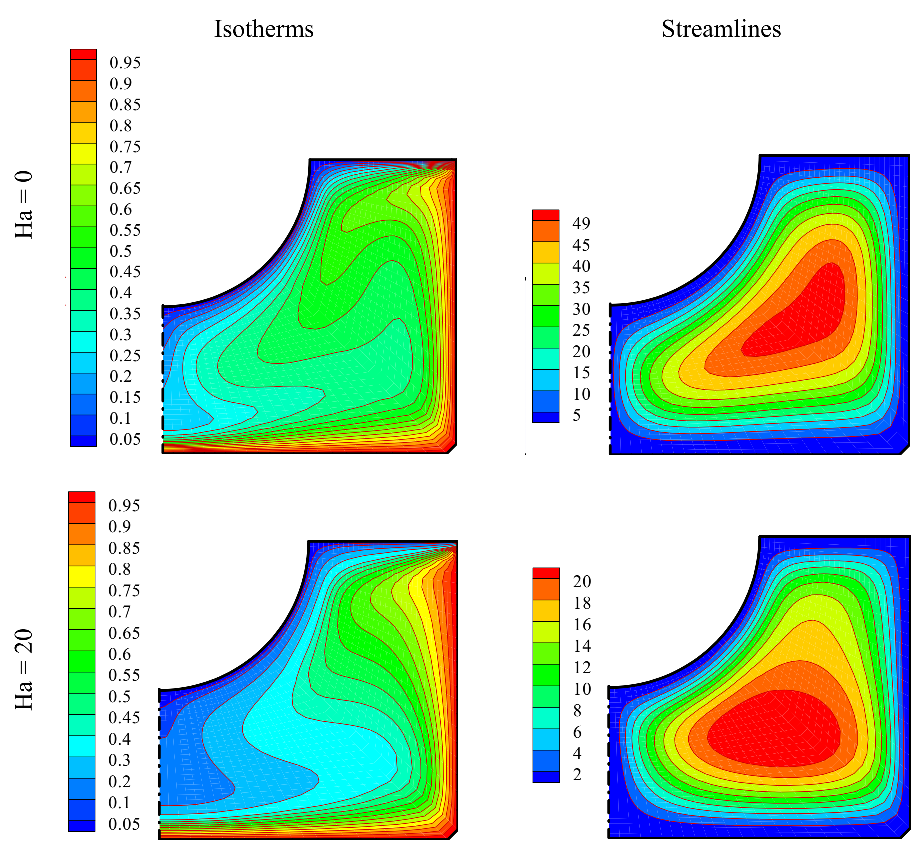

Fig. 5 Thermal and hydraulic behavior with the values of Ha at $Ra = 10^5,\ Da = 100,\ Rd = 0.8$

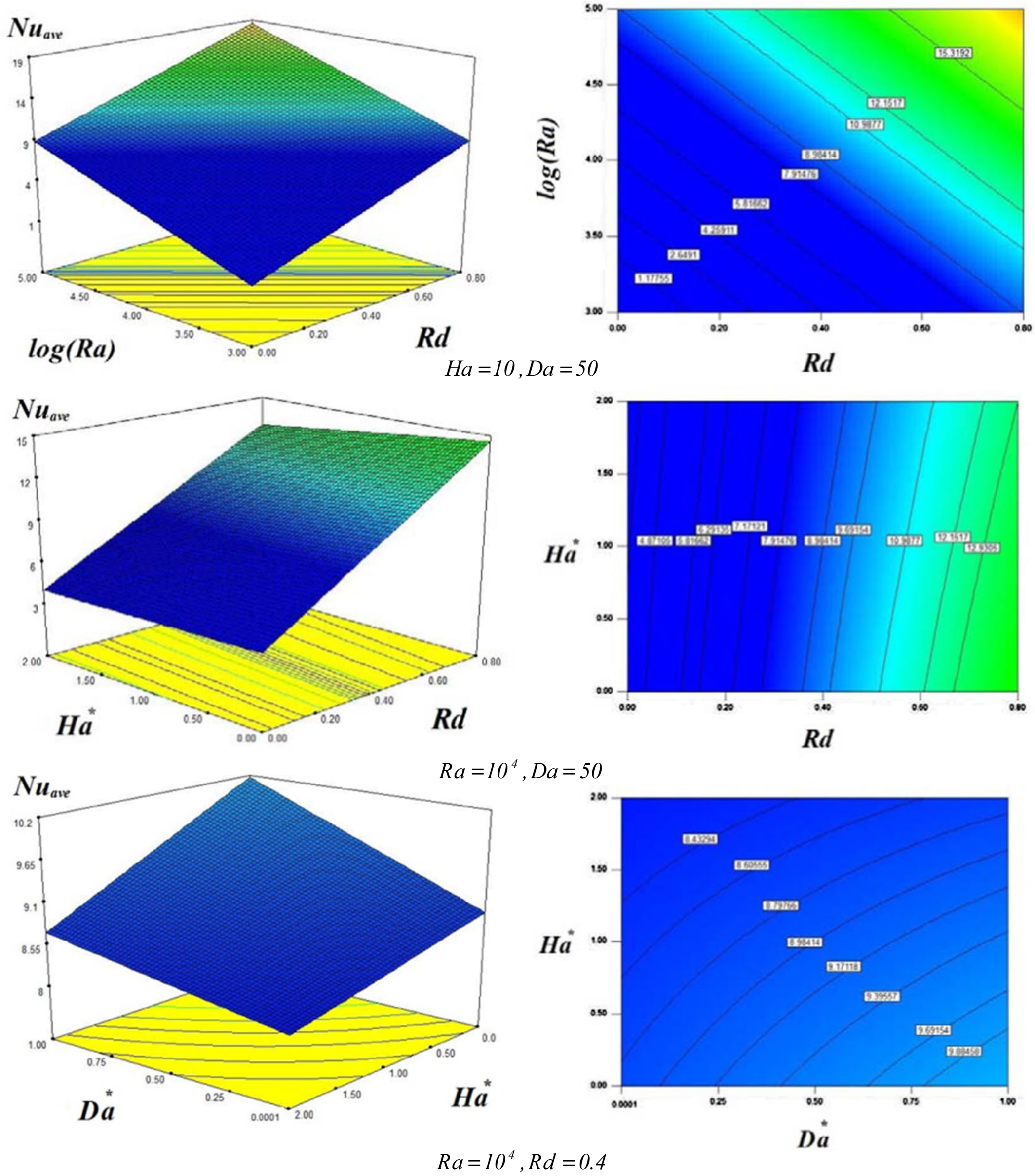

Fig. 6 Various amounts of Ra, Ha, Rd, Da and obtained Nu_{ave}

this fact can be seen in graph. Nu can be more affected by Ha when Rd has greater value. Nu does not vary with Ha in the absence of radiation (Fig. 6).

Conclusions

As an output of employment of CVFEM for application with buoyancy and Lorentz forces, new formulation for Nu was suggested in the current attempt. Nanoliquid consists of hybrid nanopowders and H_2O. Imposition of stronger Lorentz force (greater Ha) leads to decline in Ψ values, and migration of carrier fluid weakens. Consequently, ∇T declines which indicates stronger conduction. Buoyancy force impact reduces with rise of Ha, and significance of convective term reduces. Impact of Ha is insignificant when Rd = 0. Also, Nu declines with rise of Ha due to lower ∇T. As permeability intensifies, stronger vortex provides denser isotherms and thinner layer leads to higher Nu.

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