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Darcy flow and heat transfer of nanoliquid within a porous annulus with incorporating magnetic terms

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ABSTRACT

Current investigation was carried out to analyze the treatment of nanomaterial within a domain which experienced magnetic force. Outer rhombus wall is cold and the inner circle has uniform heat flux and due to these conditions, carrier fluid rotates counterclockwise. Darcy law was used for simulation and Joule heating was neglected in equations. Influences of parameters were discussed in plots and contours and CVFEM has been employed to reach such outputs. Rotational core becomes stronger with the rise of Ra while opposite results have been accomplished with the soar of Ha. In cases with higher values of shape factor, Nu has higher values and a similar trend is reported for Rd. Moreover, Nu experiences 30% reduction when Ha augments. This negative impact becomes more sensible when radiation terms are added in equations. Inclusion of nano powders has a favorable impact on Nu although it has a negative impact on temperature gradient.

1. Introduction

In the last decade, investigating the fluid stream and natural convection of nanofluid accumulated in cavities attracted more attention because their potential in heat transfers controlling in various energy systems [1–5]. Having curved walls of enclosure leading the modeling of such systems to be difficult compared to regular geometries (square or rectangle) because of grid inconsistency close to walls. From various sides of their wall, these systems can be partially cooled or heated [6–11]. Natural convection in a space between two tanks accumulated with nanomaterial was surveyed by Kashyap and Dass [12] who reported that nano-powders raised the energy performance by decreasing the irreversibility and increasing Nu; however, its increment relies on the concentration of additives. Based on the results of Aly and Raizah [13], the motion of inserting solid nanoparticles influenced intensively on the Nu and

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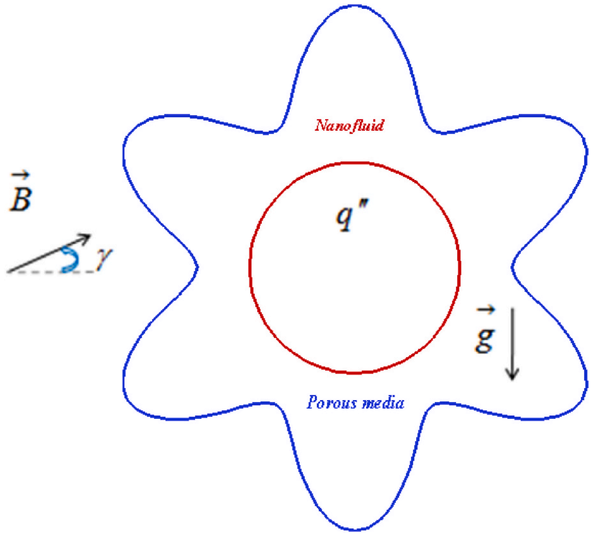

Fig. 1. Circular hot cylinder inside a rhombus.

the power of the fluid streams through a wavy cavity. Additionally, the isothermal condition and the position of the internal solid nanoparticles changed the temperature distribution and fluid stream in such cavities. To demonstrate the promising impact of nanomaterial, CNT nanoparticles were applied in solar units by Sheikholeslami and Jafaryar [14]. They reported the turbulent migration of nanomaterial. Authors investigated new approaches as numerical tools for analyzing flow [15–18]. The thermal behavior in the convective stream of nanomaterial flowing in the sinusoidal cone was analyzed by Mehmood and Iqbal [19]. The authors concluded that the maximum cooling efficiency was related to TiO2-nanoparticles while the maximum heating efficiency was related to Cu-nanoparticles. Based on the results of Bairi [20], the nanofluid saturated permeable medium raised natural convection heat transfer for a presented mixture of four affecting terms. Between numerical results and measurements, small deviations were observed.

To achieve the optimum values of geometrical factors, various soft wares were utilized [21–28]. Specifications of nanomaterial through a chamber with rectangular shape was analyzed by Jiang and Zhou [29] who concluded that for H2O–Al2O3 nanomaterial, the efficiency and the convective strength illustrated a non monotonic alteration with augmenting nano-powder concentration; nonetheless, for PGW-ZnO, they were reduced monotonously. Furthermore, under various concentrations, the entropy generation and the stream specifications were investigated comprehensively. The convective migration of Newtonian nanomaterial was analyzed by Polidori et al. [30] who examined the nature of the nanofluid. Based on their results, viscosity played the main role in the behavior of operating fluid. Recently hybrid nanomaterials have become popular due to their high thermal feature and one of the good works about the application of such material within the solar system has been published by Sheikholeslami [31]. He applied an innovative disturber to find better mixing of hybrid nanofluid. Changing the operating fluid and geometry of chambers were suggested in various applications [32,33]. Empirically, the impacts of nanoparticle deposition on the heat transfer rate were analyzed by Shen et al. [34] (under the impact of ultrasound and forces between nanoparticles). They reported that the efficiency decreased when the heat flux grew. The free convection of nanofluid within a square tank has been investigated by Wang et al. [35] who found that the main reason for increased convection was the random motion of the nanoparticles at low Re.

Purpose of the current investigation is to simulate the nano-powder migration due to Lorentz forces within a permeable media. To simplify the Navier Stokes, Darcy model was used and formulation was changed to vorticity form. Induced magnetic was neglected and external force can affect the velocity directly. The CVFEM approach helped us to simulate this scientific model and outcomes were derived as contours and graphs to demonstrate the impact of radiation, buoyancy and Lorentz terms.

2. Problem explanation

Circular hot cylinder inside a cold wavy cylinder has been striated and created the domain of current paper (as demonstrated in Fig. 1). Carrier fluid is a nanomaterial which consists of Al2O3 and H2O and properties are the same as [36]. In addition various shapes of powders were employed. Outer wall has T = 0, whereas the circular wall has uniform heat flux. Due to neglecting joule heating, Lorentz forces just affect the momentum and Darcy law makes the equations simpler. In this approach, the advection terms in momentum have been neglected [37]. Walls are impermeable and a single phase model was selected. Ro calculate the density, Boussinesq approach was utilized. At last, CVFEM was implemented to solve the equations which can summarize as [36]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\mu_{nf}}{K}u=-\frac{\partial P}{\partial x}+\sigma_{nf}B_0^2\left[(\sin\gamma)v(\cos\gamma)-u(\sin\gamma)^2\right] \tag{2}$$

Table 1
Nu_{ave} values for various resolution of grids.

$Ra = 600, Rd = 0.8, Ha = 20\ and \varnothing = 0.04$	41×121	*4.4715*
	81×241	*4.4987*
	61×181	*4.4842*
	71×211	*4.4977*
	51×151	*4.4896*

$$\begin{aligned}\frac{\partial P}{\partial y} &= \beta_{nf}(T - T_c)\rho_{nf} g - \frac{1}{K} v\mu_{nf} \\ &+ \sigma_{nf} B_0^2 (\cos\gamma)[(\sin\gamma)u - (\cos\gamma)v]\end{aligned} \tag{3}$$

$$\frac{1}{(\rho C_p)_{nf}}\frac{\partial q_r}{\partial y} + \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k_{nf}(\rho C_p)_{nf}^{-1}\left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial x^2}\right) \tag{4}$$

To improve the performance of the unit and reduce the irreversibility, we added nano powders of alumina into H_2O to create new carrier fluid [36] and for calculating properties we utilized empirical data [36]. Additionally, shape factor impact on k_{nf} was added. Brownian effect has been added in calculation of μ_{nf} [36]:

$$\begin{aligned}\mu_{eff} &= \mu_{static} + \frac{\mu_f}{\Pr_f}(k_f / k_{Brownian})^{-1} \\ k_{Brownian} &= 5 \times 10^4 c_{p,f}\rho_f g'(d_p, \varphi, T)\varphi\sqrt{\frac{\kappa_b T}{\rho_p d_p}}\end{aligned} \tag{5}$$

While for k_{nf} can be measured with adding influences of shape coefficient [36]:

$$\frac{k_{nf}}{k_f} = \frac{k_f + (k_p - k_f)\varphi + \varphi(k_p - k_f)m + k_p + k_f m}{mk_f + (k_f - k_p)\varphi + k_f + k_p} \tag{6}$$

To achieve the dimensionless for of equations, below definitions were utilized [36]:

$$\Psi = \psi \Big/ \alpha_{nf}, \theta = \frac{T - T_c}{\Delta T}, \Delta T = \frac{q'' L}{k_f}, (Y, X) = (y, x) \Big/ L \tag{7}$$

So, the equations are [36]:

$$\begin{aligned}\frac{\partial^2 \Psi}{\partial Y^2} + \frac{\partial^2 \Psi}{\partial X^2} = -Ha\frac{A_6}{A_5}\left[(\cos\gamma)\frac{\partial^2 \Psi}{\partial X^2}(\cos\gamma) + 2\frac{\partial^2 \Psi}{\partial X \partial Y}(\sin\gamma)(\cos\gamma) + \frac{\partial^2 \Psi}{\partial Y^2}(\sin^2\gamma)\right] \\ -\frac{A_3}{A_4}\frac{A_2}{A_5}\frac{\partial \theta}{\partial X} Ra\end{aligned} \tag{8}$$

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

The mentioned variables in Eqs. (8) and (9) are [36]:

$$\begin{aligned}Ra &= \frac{g\, K\, (\rho\beta)_f L\, \Delta T}{\mu_f\, \alpha_f}, Rd = 4\sigma_e T_c^3 \Big/ (\beta_R k_f) \\ A_1 &= \frac{\rho_{nf}}{\rho_f}, A_2 = \frac{(\rho C_P)_{nf}}{(\rho C_P)_f}, A_5 = \frac{\mu_{nf}}{\mu_f}, \\ A_3 &= \frac{(\rho\beta)_{nf}}{(\rho\beta)_f}, A_6 = \frac{\sigma_{nf}}{\sigma_f}, A_4 = \frac{k_{nf}}{k_f}, Ha = \frac{\sigma_f}{\mu_f} K B_0^2,\end{aligned} \tag{10}$$

One of the strongest methods for simulation of convective flows is CVFEM which is nominated by Sheikholeslami [37] and his publications prove its nice accuracy. In generation of the grid, finite element approaches were involved while in integrating the equations the same approach of finite volume has been employed. Upwind approach for discretizing the advection terms was utilized. Weighting functions help this approach to employ multi physics. Using the shape function for predicting the gradient of scalars is a good option for this method. Criterion for residuals is 10-5 for all scalars and upwind method was utilized for advection. As illustrated in Table 1, using finer mesh than the 3rd case is not suggested because no variation appears in Nu values. To recognize the thermal intensity, below parameter was defined:

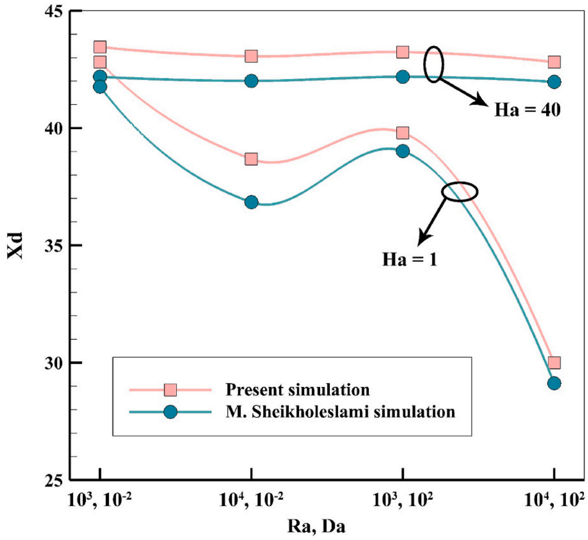

Fig. 2. Compassion for free convection with previous data [37].

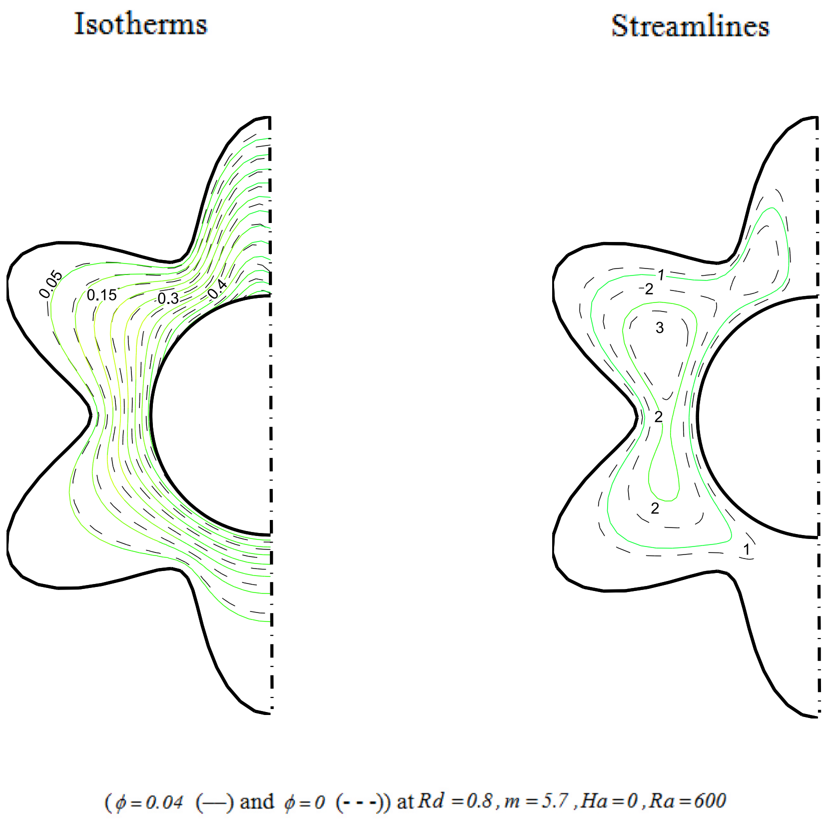

Fig. 3. Inclusion of nanomaterial and obtained contours.

$$Nu_{loc} = \frac{1}{\theta}\left(1 + \frac{4}{3}\left(\frac{k_{nf}}{k_f}\right)^{-1} Rd\right)\left(\frac{k_{nf}}{k_f}\right), Nu_{ave} = \frac{1}{S}\int_0^s Nu_{loc}\, ds \tag{11}$$

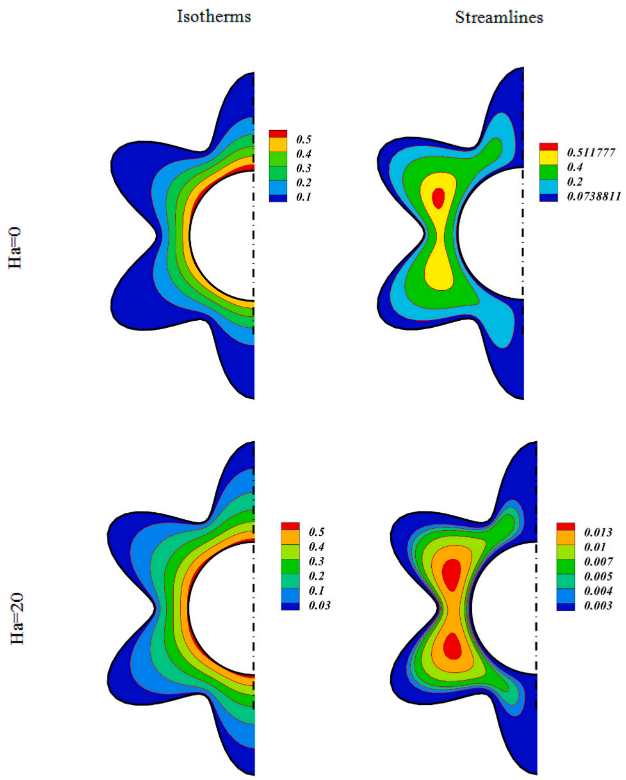

Fig. 4. Insert of magnetic force and reported contours at $m = 5.7, \varphi = 0.04, Ra = 100, Rd = 0.8$

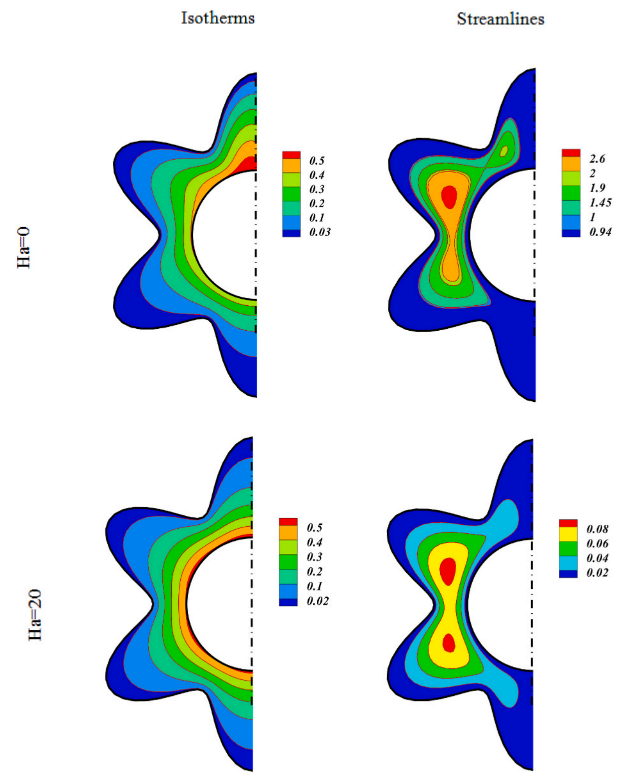

Fig. 5. Insert of magnetic force and reported contours at $Rd = 0.8, m = 5.7, \varphi = 0.04, Ra = 600$

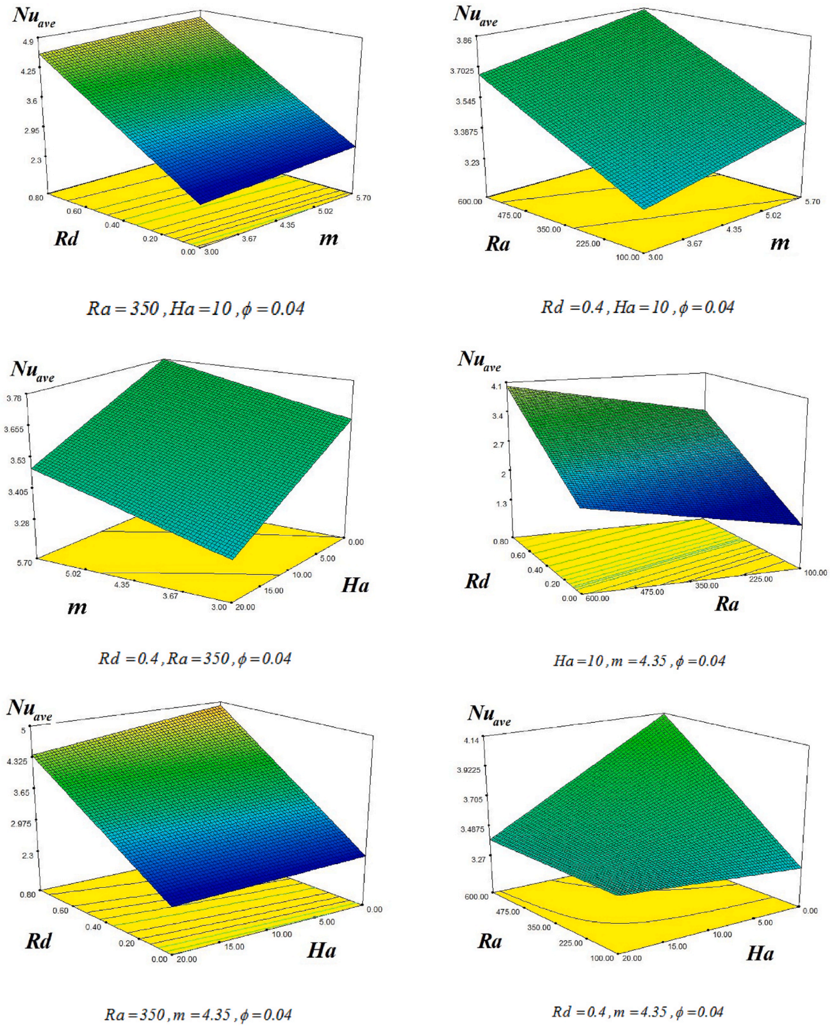

Fig. 6. Changing variables and calculated Nu.

3. Results and discussion

In this article, laminar transportation of nanomaterial was scrutinized by employing radiation impact. CVFEM is the best tool for simulation for MHD flow especially when vorticity formulation has been used to simplify the equations. Due to symmetric boundary conditions, just modeling half of geometry is enough. Validity of present procedure should be checked and Fig. 2 belongs to this purpose. We can ensure our procedure is accurate and outputs are trustable [37]. Treatment of carrier fluid and style of flow change as a result of adding nano powders and these phenomena were demonstrated in Fig. 3. As concentration of particles augments, carrier fluid movement enhances and iso-temperature suits are more disturbed. Therefore, power of the main eddy augments and temperature gradient improves. This phenomenon is attributed to greater thermal conductivity which can affect the treatment of carrier fluid. In addition, it may be concluded that augmenting Ha can augment the influence of this factor because of this fact that both factors are the same direct in view of conduction mode.

Several simulations were conducted to demonstrate the influence of Ra and Ha as illustrated in Figs. 4 and 5. Inner circle is warm and after the nanomaterial becomes warmer it goes to the upper side and then moves downward along the rhombus and creates a counter clockwise cell. Reduction of density is the main reason for generating buoyancy force which elevates the fluid. Flow direction along the rhombus is downward and for small Ra, isotherms were almost parallel to each other. At Ra = 100, insertion of Ha does not change the position of the center of the core while it reduces the power of cell and temperature of circle augments which means lower Nu. As Ra augments from 100 to 600, Y value increases about 3.9 times and the main cell converts to two smaller ones and stretches along the outer wall. Generation of isotherms proves the stronger buoyancy force and temperature of the inner surface reduces. Isotherms are disturbed more with augment of Ra. At Ra = 600, as Ha augments from 0 to 20, the power of the cell reduces about 95% and thermal plume diminishes. Following the configuration of the inner wall means the dominance of conduction when Ha = 20.

For investigating the role of scrutinized variables of the current model on Nu, we demonstrated Fig. 6 in which variations of Nu were presented. In addition, to show the mathematical format of output, the below formula can be implemented respect to various values of parameters:

$$\begin{aligned} Nu_{ave} &= 2.68 + 0.06m + 0.91Rd + 0.42Ra - 0.33Ha \\ -Ha(0.41)Ra &+ 1.2 \times 10^{-2} Ha\, m - 0.21 Rd\, Ha + 2.3 \times 10^{-4} m^2 \end{aligned} \tag{12}$$

As it is clear from the above equation, the variation is not linear and all factors can change the Nu. Among various parameters, m has the lowest effect as depicted in the graph. As Lorentz augments, Nu experiences a reduction of about 30% when Rd = 0.8 and its impact reduces when radiation impact is removed from equations. Due to changing heat flux, the formula of Nu changes and influence of Rd was added in definition and as it can be observed in graphs, greater values of Nu can be achieved with increasing in Rd. Presence of Ha reduces the positive impact of buoyancy force and when Ha = 20, influence of Ra can be neglected in variation of Nu. Favorable impact of "*m*" will not change with augment of Ha and augmenting "m" provides greater "k_{nf}" and helps the conduction mode. Besides, changing Rd cannot affect the influence of shape factor. Impose of Lorentz slows the movement of nano powders and boundary layer distance from solid augments. Strength of buoyancy forces reduces and its contribution reduces when Ha augments and distortion of isotherms reduces which is attributed to conduction dominance.

4. Conclusions

Radiation term influence was involved in the mathematical model of nanomaterial hydrothermal migration within a porous tank. Darcy law and stream function definition help us to reach a simpler model and CVFEM can solve it with high accuracy. Outputs were illustrated by drawing contours and 3D graphs based on various parameters. It is clear from outputs that dominance of convective takes place for greater Ra. Temperature in the vicinity region of the inner surface reduces with soar buoyancy force and the opposite trend was calculated for Lorentz force. Due to more intense isotherm with augment of shape coefficient, bigger Nu has been evaluated for cases with platelet nano powders. The flow structure alters and the cell shifts downward with insert of magnetic force. Reduction of Nu happens about 30% if Lorentz force imposes and the inner wall experiences greater temperature.

Author statement

Ying-Fang Zhang: Formal analysis; Validation; Nidal H. Abu-Hamdeh: Supervision; Conceptualization; Ziyad Jamil Talabany: Investigation; Validation; Mohammed N. Ajour: Methodology; Investigation; Randa I. Hatamleh: Software; Methodology; Awad Musa: Writing – review & editing; Software

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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