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ORIGINAL ARTICLE

Solar radiation impact on ferrofluid convection with applying electric field

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Abstract
For estimating impact of electric force on treatment of ferrofluid, new numerical technique have been involved in current article. The operate fluid contains iron oxide as additive in nano-sized with various shapes. The fraction of particles with nano-sized is smaller than 0.06, and for involving such effect, properties of carrier fluid have been changed based on empirical formulation with neglecting the slip velocity. There were two moving wall at the left and bottom surfaces which has highest temperature and voltage. The domain was porous and related terms were added in momentum according to non-Darcy assumption. Combined method of FVM and FEM was selected to find the solution for this problem. As electric force applied, the nanofluid can move with higher speed and two primary vortex convert to one stronger vortex. Nu augments about 125.52% and 65.43% with rise of voltage when Da = 1e2 and 1e5. Utilizing media with higher permeability lead to stronger collision with wall and Nu elevates about 113.29%. Replacing nanoparticle with higher shape factor instead of sphere, Nu augments about 3.69%.

Keywords Ferrofluid · Electric filed · Permeable container · Radiation · Electrode · Heat transfer

Introduction

Heat transfer rate and natural convection stream inside a container are faced in an extensive range of industrial and engineering uses including food processing, electronic system cooling, and solar energy collectors (Chu et al. 2020a; Valipour et al. 2018; Tong et al. 2019; Qin 2021a; Yan et al. 2021). In these uses, it is significant to regard the impacts of magnetic field and nanoliquid on liquid stream and heat transfer rate in a container of various configurations with different heat boundary conditions (Chu and Bach 2020; Babazadeh et al. 2020; Yu et al. 2021b; Wang et al. 2021; Chu et al. 2020e). As the liquid is electrically conducting and exposed to a magnetic field, the liquid observes a Lorentz force interacting with the buoyancy power in governing the temperature and stream field (Yao et al. 2021; Valipour et al. 2017; Chen et al. 2020a; Chu et al. 2020f; Qin 2021b). Nanoliquids have been defined as a novel and attractive kind of nanotechnology-based heat transfer fluids, and heave significantly been improved in the last years (Chen et al. , 2020b; Feng et al. 2021; Manh et al. 2019; Budak et al. 2021; Wang et al. 2022). The nanoliquids are a mixture of typical fluids with nano-powders illustrating great range of heat transfer (Chu et al. 2020b, c; Qin 2021c; Huang et al. 2021; Ouyang et al. 2021). Convection of nanoliquid inside an inclined hole considering a heater was surveyed by Sheremet and Pop (2018). Their observations indicated that convective stream attenuation and heat transfer increment as the distance between the cold vertical side and the heater decreases. Alsabery et al. (2019) surveyed the impact of nanoliquid on combined convection through a container. Their observations indicated that a growth of the mean Nu at

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the hot side relies on the traveling terms and heat transmission strength reduces with the undulations number and also the internal solid cylinder parameter.

Hashim et al. (2019) surveyed the natural convection through a wavy container accumulated with nanoliquid and regarding Buongiorno's simulation. Their observations indicated that Nu in hole is raised with defining nano-powders and a choosing of optimal number of vibrations. Some papers were investigated different stuffs to extend the productivity of unit (Tan et al. 2021; Guo et al. 2021; Chu et al. 2020d,g; Ali et al. 2021; Qin 2021d). Wu and Rao (2017) applied LBM for copper/H_2O nanoliquid to model the free convection to develop the cooling efficiency of BTM. They proved that impose of copper nano-powders can grow the cooling efficiency and reduce the temperature difference of the considered medium. Researchers of Ref. (Sheremet et al. 2017) surveyed the nanoliquid free convection within a porous hole regarding the impact of heat dispersion. Their observations indicated that Nu grows with undulation and dispersion term whereas the convective stream is abated with augmentation of undulation. The fluid migration inside a heated porous hole accumulated with nanoliquid was surveyed by Chamkha and Ismael (2014). Their observations indicated that with using the nanoliquid, Nu can be raised. Their observation indicated that as $Ra \leq 10^5$, Nu has greatest value for special thickness of porous layer. The mass and heat transportation of nanoliquid were scrutinized by Atif et al. (2019) in appearance of MHD and they indicated that the strengthening amounts of the generalized Biot number raise the dimensionless curve of the temperature. Khan et al. (2018) scrutinized irreversibility of stretched surface for nanoliquid. Their observation indicated that the irreversibility relies on heat irreversibility, and concentration irreversibilities, and viscous dissipation. The author of Ref. (Hayat et al. 2018) scrutinized the influence of homogeneous–heterogeneous chemical parameters on the mass transfer in nanoliquid inside a porous body. Their observation indicated that a growth in this term illustrates analogous trend for both thermophoresis and temperature terms. Several investigations were offered new techniques to improving the productivity (Yu et al. 2021a; Li et al. 2021; She et al. 2021; Yadav et al. 2021). Waqas et al. (2021) surveyed the impacts of radiation on bioconvection stream of nanoliquid involving thermal source–sink on a stretching plate. Their observations indicated that the velocity can be grown with a combined convection parameter. Aldabesh et al. (2021) surveyed the axisymmetric investigation for Casson nanosubstance because of two parallel stretchable discs. Their observations indicated that when the amount of thermophoresis term and the Biot number increased, the concentration increases and also concentration profile diminishes because of growth in the amount of Brownian motion term.

With considering previous articles, it can be concluded that external force such as electric force can have promising effect on convective mode. Besides, applying nanomaterial can elevate the conductive mode. In current study, for improving the nanomaterial convective mode within a permeable container, EHD has been applied. One source term for radiation was added in energy equations and two source terms for EHD and permeability were added in momentum. CVFEM was applied for modeling and verification was presented according to the previous article with same numerical approach. Shape of nano-powder was selected as another factor which can change the behavior of the system.

Description of system

For improving the convective behavior of system, electric field has been applied as described in Fig. 1. The carrier fluid is Ethylene glycol–Fe_3O_4 and to evaluate the properties, the formulations existing in Ref. (Sheikholeslami and Seyednezhad 2018) have been applied. The media are permeable and to derive source terms, non-Darcy technique was exploited. Various shapes were considered for nano-sized particles with involving homogeneous approach. With adding source terms in basic equations, the following equations were derived (Sheikholeslami and Seyednezhad 2018):

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

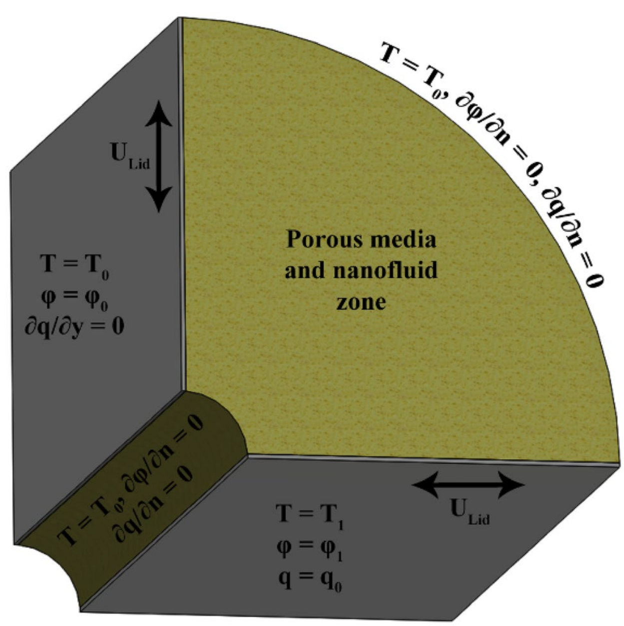


Fig. 1 EHD flow within a container with circular walls

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

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

$$q = \nabla.\varepsilon\vec{E}. \tag{4}$$

For finding the behavior of system, the following equations need to solved (Sheikholeslami and Seyednezhad 2018):

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

To make the formulation in non-dimension form, the following equations were applied (Sheikholeslami 2018):

$$\begin{cases} \nabla.\vec{V} = 0, \; q = \nabla.\varepsilon\vec{E}, \\ q\dfrac{S_E}{\rho_{nf}/\rho_f}\vec{E} + \dfrac{\rho_{nf}/\rho_f}{\mu_{nf}/\mu_f}\nabla^2\vec{V}\dfrac{1}{\mathrm{Re}} - \nabla p - \dfrac{\mu_{nf}}{\mu_f}\left(\dfrac{\rho_{nf}}{\rho_f}\right)^{-1}\vec{V}\dfrac{1}{\mathrm{Re}\,Da} = \left(\left(\vec{V}.\nabla\right)\vec{V} + \dfrac{\partial\vec{V}}{\partial t}\right) \\ \left(\dfrac{\partial\theta}{\partial t} + \theta\left(\vec{V}.\nabla\right)\right) = \dfrac{k_{nf}/k_f}{\left(\rho C_p\right)_{nf}/\left(\rho C_p\right)_f}\nabla^2\theta\dfrac{1}{Pr\mathrm{Re}} + \dfrac{4}{3}\left(\dfrac{k_{nf}}{k_f}\right)^{-1}Rd\dfrac{\partial^2\theta}{\partial Y^2} + S_E\dfrac{\left(\rho C_p\right)_f}{\left(\rho C_p\right)_{nf}}Ec\left(\vec{J}.\vec{E}\right) \\ \nabla.\vec{J} + \dfrac{\partial q}{\partial t} = 0, \vec{E} + \nabla\varphi = 0, \end{cases} \tag{6}$$

$$\begin{aligned} &\overline{q} = \frac{q}{q_0}, \theta = \frac{T - T_0}{\nabla T}, \left(\overline{y}, \overline{x}\right) = \frac{(y, x)}{L}, \\ &\overline{p} = \frac{p}{\rho U_{Lid}^2}, \overline{E} = \frac{E}{E_0}, \overline{t} = \frac{tU_{Lid}}{L}, \\ &\overline{\varphi} = \frac{\varphi - \varphi_0}{\nabla\varphi}, \left(\overline{u}, \overline{v}\right) = \frac{(u, v)}{U_{Lid}}, \\ &\nabla T = T_1 - T_0, \nabla\varphi = \varphi_1 - \varphi_0. \end{aligned} \tag{7}$$

The above equations are very complex, and to simplify the momentum equations, vorticity formulations' form has been utilized (Sheikholeslami 2018):

$$\begin{aligned} &\frac{\partial\psi}{\partial y} = u, \Omega = \frac{\omega}{LU_{Lid}}, v = -\frac{\partial\psi}{\partial x}, \\ &\Psi = \frac{\psi L}{U_{Lid}}, \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \end{aligned} \tag{8}$$

Local and average Nu must be defined as follows:

$$Nu_{loc} = \left(\frac{k_{nf}}{k_f}\right)\left(1 + \frac{4}{3}Rd\left(\frac{k_{nf}}{k_f}\right)^{-1}\right)\frac{\partial\Theta}{\partial X} \tag{9}$$

$$Nu_{ave} = \frac{1}{L}\int_0^L Nu_{loc}\,dY. \tag{10}$$

CVFEM has been applied to discover the solution of the above equations. The utilized fluid is nanomaterial which contains iron oxide nano-powders with various shapes. The mentioned method was introduced by Sheikholeslami (2018) for simulating the various physics. FORTRAN code was written to simulate the process and verification test have been mentioned in next step.

Results and discussion

Applying permeable media for container filled with nanomaterial is helpful in view of convective behavior of a system. Impose of electric force makes convection to become more significant. In current simulation, impacts of permeability and electric force on treatment of ferrofluid have been investigated. The container has two lid walls which has highest temperature and positive electrode. All surfaces are stationary and have zero gradient of q except the bottom surface. The highest and lowest values of voltage at bottom and left walls indicate the negative and positive electrodes. All surfaces are cold except the bottom wall and buoyancy force has been involved in equations. The complex form of equations needs powerful numerical approach to capture the details of such new source. CVFEM was chosen to this purpose in this investigation. The amount of electric force in various spaces is not uniform and Fig. 2 depicts the variation for this factor. The variations of q in two cases were demonstrated in this graph. As anticipated, the biggest value belongs to zone near the bottom wall and minimum values occur at upper side of outer wall. At biggest value of Da, the distortion of contour is more sensible. It should be verified that the present code has capability for simulating free convection of nanofluid in existence of external force. Therefore, the code was prepared according to conditions of Ref. (Sheikholeslami 2019) and Fig. 3 was derived according to simulation data. The achieved data indicate nice accommodation of current code. The operate fluid of current article is iron oxide–Ethylene glycol and various shape of nano-sized material has been utilized. Homogeneous mixture for ferrofluid was considered incorporating experimental correlations. The role of radiation term has been imposed in energy equation. To obtain the best grid, Nu for various size of grid has been utilized and one example is reported in Table 1. Impacts of shape factor, permeability and voltages were demonstrated in this section.

The significant outputs which can show the treatment of ferrofluid within various conditions are streamline and isotherms. The distribution of temperature and strength of streamline have been shown in Figs. 4, 5, 6 and 7, respectively. Two figures belong to state of absence of EHD and the other show the behavior in existence of such source. When voltage is zero, two eddies generate inside the domain near the lid walls. The both eddy rotates in same direction. As permeability augments, the eddies merge together and the new eddy power is higher than primary eddy. The influence of thermal plume becomes more sensible with growth of Da. Augmenting permeability lets the ferrofluid move faster and shape of isotherms become more complex owing to higher convection. Augmenting the voltages makes the velocity of fluid to increase and stronger vortex can appear. Given Da = 1e2, with apply of EHD, there is one vortex within the domain. Augmenting Da in presence of EHD cannot change the number of eddy. More resistance with wall can be observed if Da and voltages increase. To measure the cooling rate of hot wall, Nu has been calculated over this wall and based on obtained data, the following formulation has been obtained:

$$Nu_{ave} = 6.75 + 0.31m + 2.86\Delta\varphi + 3\log Da + 2.89Rd \\ +0.59\Delta\varphi(\log Da) + 1.04(\log Da)Rd - 15 \times 10^{-3}m^2. \tag{11}$$

The influences of all factors are involved in this formula. Figure 8 demonstrates the impacts of scrutinized factors on Nu. To depict the impact of form of nano-sized powders, shape factor (m) was involved in formulation of k_{nf}. Adding additive can enhance the cooling rate. In addition, existence of nanoparticles makes it possible to employ electric field. As m rises from 3 to 5.7, 4.8 and 3.7, Nu rises around 3.69%, 2.54% and 1.03%. The platelet shape has biggest value and for investigating other factors, such shape has been selected. To involve the radiation effect of surrounding, one term was added in temperature equations and this effect should be added in definition of Nu, too. Adding such effect can increase the cooling rate and Nu enhances about 82.27% with elevation of Rd. To employ permeable media in equation, one term in each direction has been added in

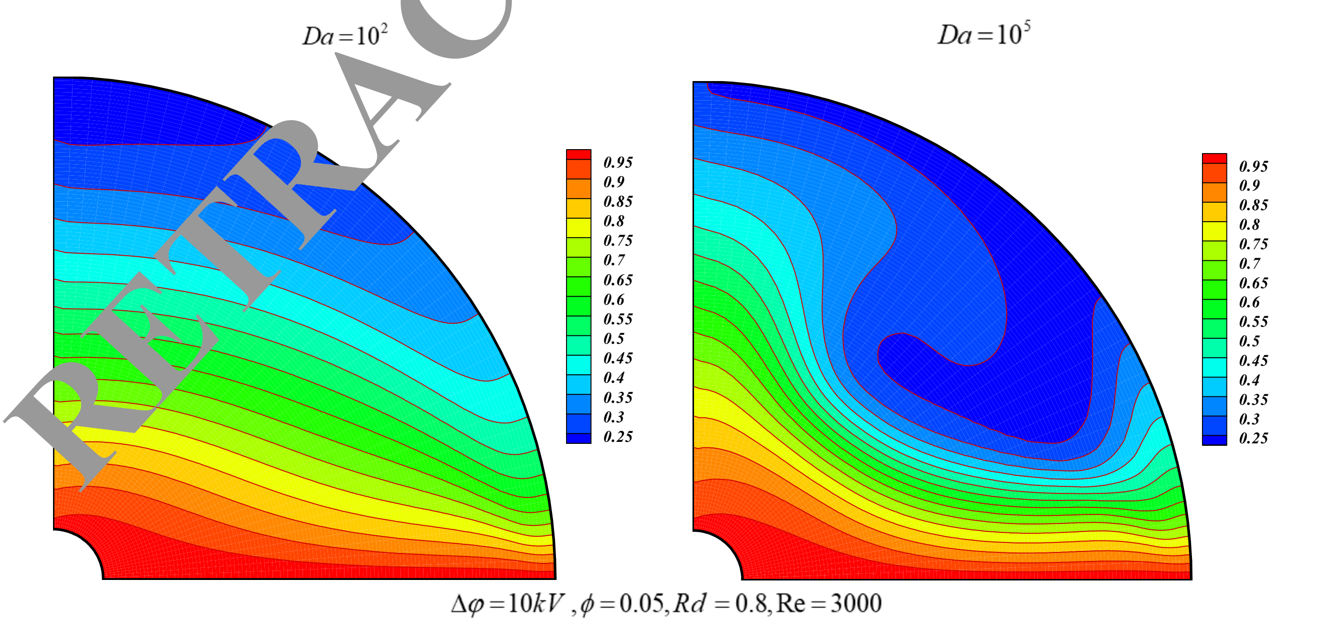


Fig. 2 Outputs for electric density within the domain

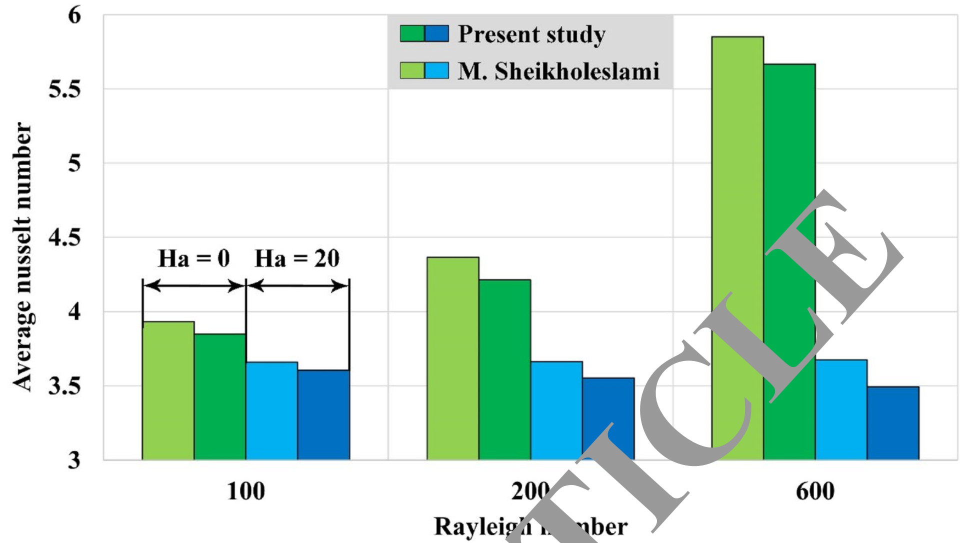


Fig. 3 Checking the accuracy of technique according to Ref. (Sheikholeslami 2019)

Table 1 Selecting optimized grid according to Nu

$RD=0.8$, $Re=3000$, $Da=10^5$, $\Delta\varphi=10$, $\varnothing=0.05$					
51 × 151	61 × 181	71 × 211	81 × 241	91 × 271	101 × 301
17.21428	17.21822	17.22258	17.22883	17.22905	17.22957

momentum. Such approach is named by non-Darcy. When the media with greater permeability have been utilized, ferrofluid can move easier within the domain. More collision with walls offers higher cooling rate and Nu augments about 113.29% with elevation of Da. The most significant factor of current study is $\Delta\varphi$ and with rise of voltage, this factor augments. With application of EHD, the induced force makes the speed of ferrofluid to increase. As this factor grows, Nu enhances about 125.52% and 65.43% when Da = 1e2 and 1e5. Imposing such force can be considered as promising way which can enhance the cooling rate.

Conclusions

To enhance the convection within a container with bottom lid wall, EHD impact has been involved in this study. The container is filled with mixture of Ethylene glycol and iron oxide with various shapes of particles. The left wall was assumed as negative electrode and bottom wall has greatest electrical density. The variations of density indicate the non-uniform source term and such results were demonstrated in results. Low concentration of ferrofluid proves the correctness of assumption of single phase. Existence of complex source term and new scalars for calculating voltages and density of electric field create complex equations and solving such model needs powerful technique. CVFEM was chosen for this aim and verification for predicting the behavior in existence of external force was presented. The bottom wall was hot and it has greatest q and voltages, thus, it is positive electrode. Changing the properties of nanomaterial is enough to involve nanofluid effect because of low fraction of additive. Involving the permeable media was done via non-Darcy model. Influences of shape of nano-powders, permeability, and strength of EHD were exhibited in results. As voltage increases, the strength of thermal plume enhances and fluid moves with greater speed. Nu increases about 125.52% and 65.43% when Da = 1e2 and 1e5. It is clear that the impact of voltage for lower permeability case is more sensible. The container is made from porous material and utilizing higher permeability enhances the speed of operate fluid. Augment of Da in absence of EHD makes streamline style significantly and two small eddies merge together and create one new stronger eddy. All eddies rotate clockwise. Nu elevates about 113.29% with augment of permeability. Adding iron oxide can intensify the conductivity of operate fluid which results higher convection. Shape of nano-powder can change conductivity of ferrofluid and shape factor (m) was utilized to show the impact of nanoparticle shape. As m rises from 3 to 5.7, 4.8 and 3.7, Nu elevates by 3.69%, 2.54% and 1.03%.

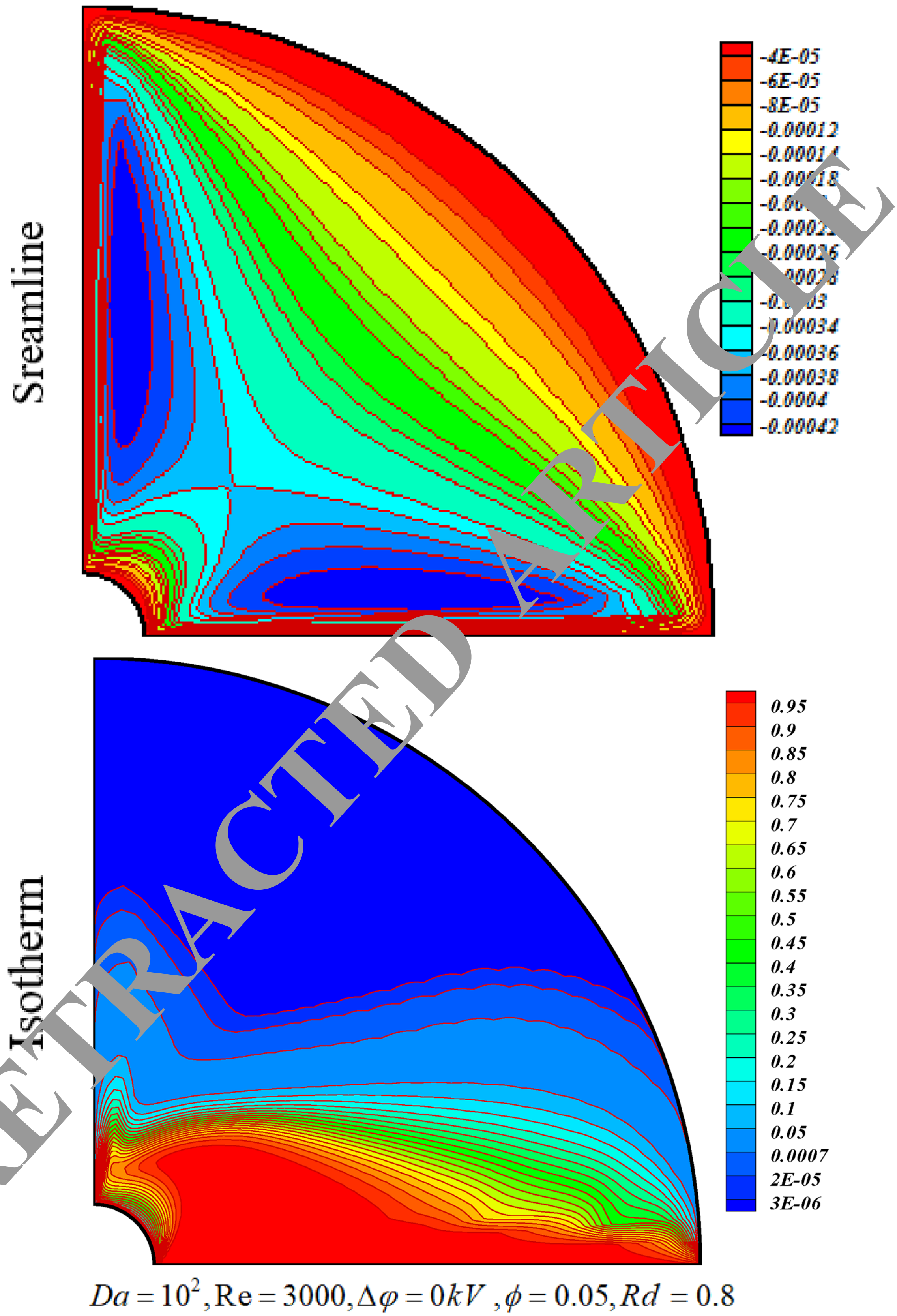


Fig. 4 Outputs for lowest values of factors

Fig. 5 Behavior of system in highest Da and lowest other factors

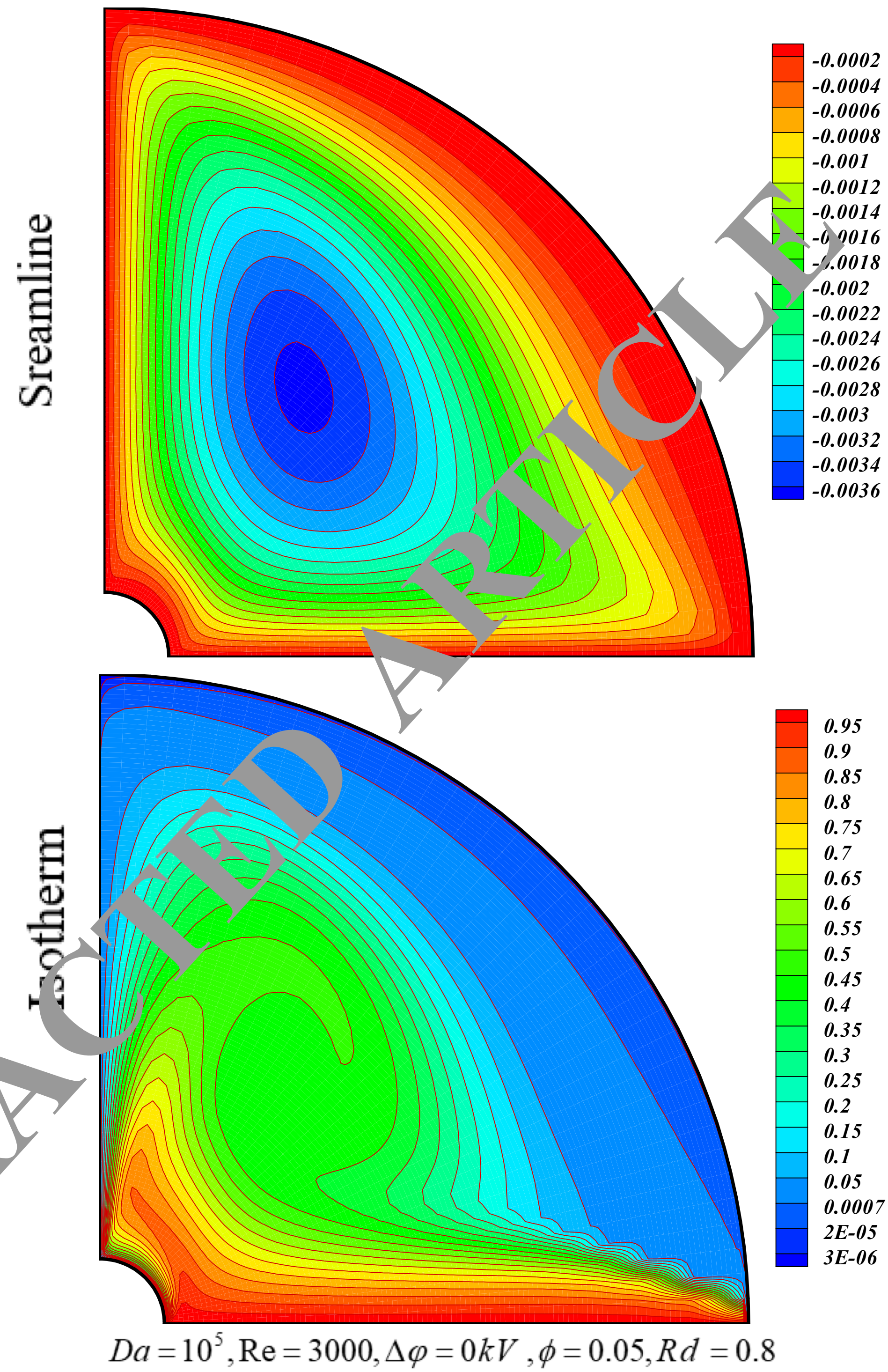


Fig. 6 Highest voltage and obtained contours

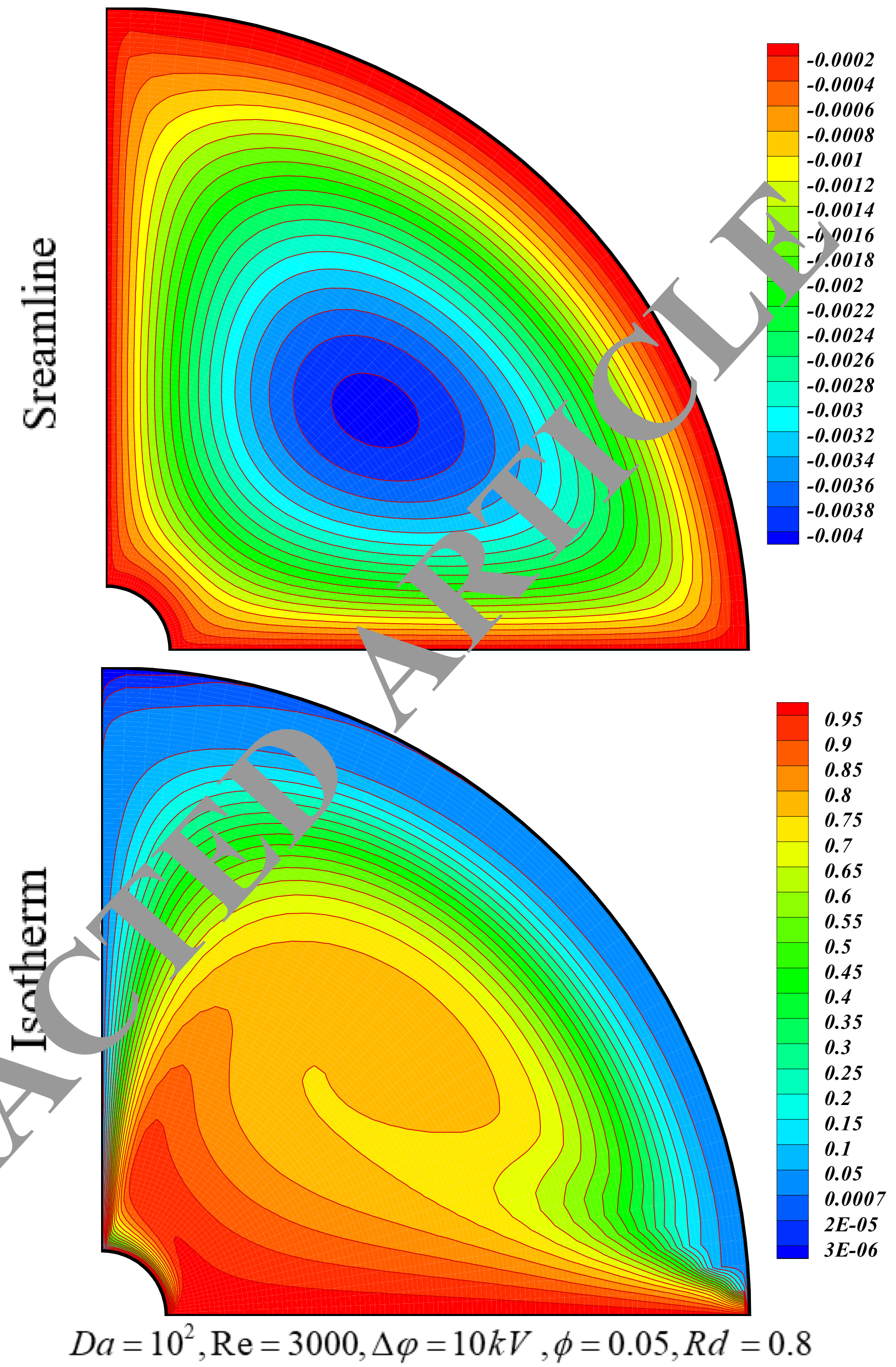
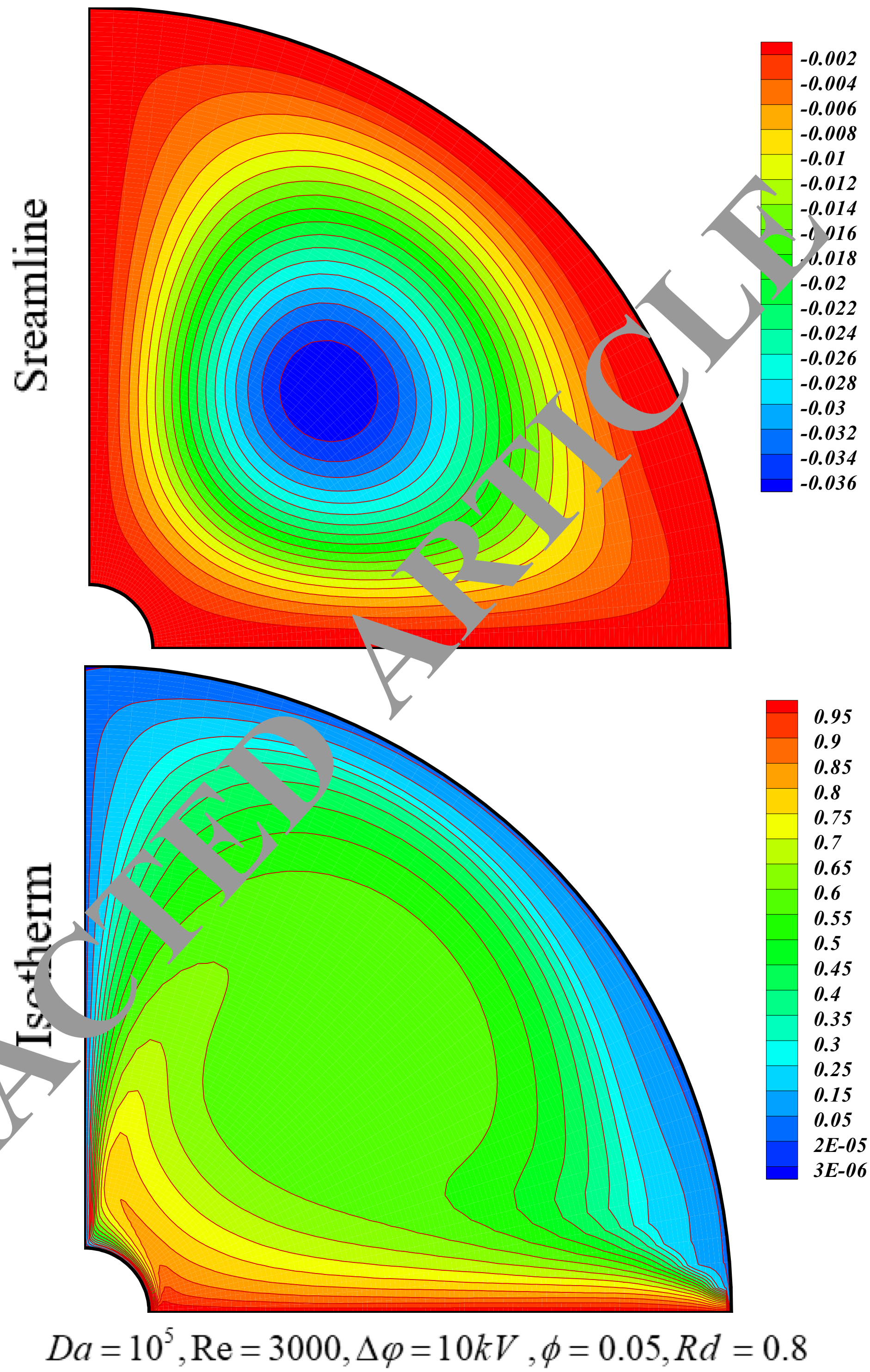


Fig. 7 Treatment of ferrofluid for greatest values of variables



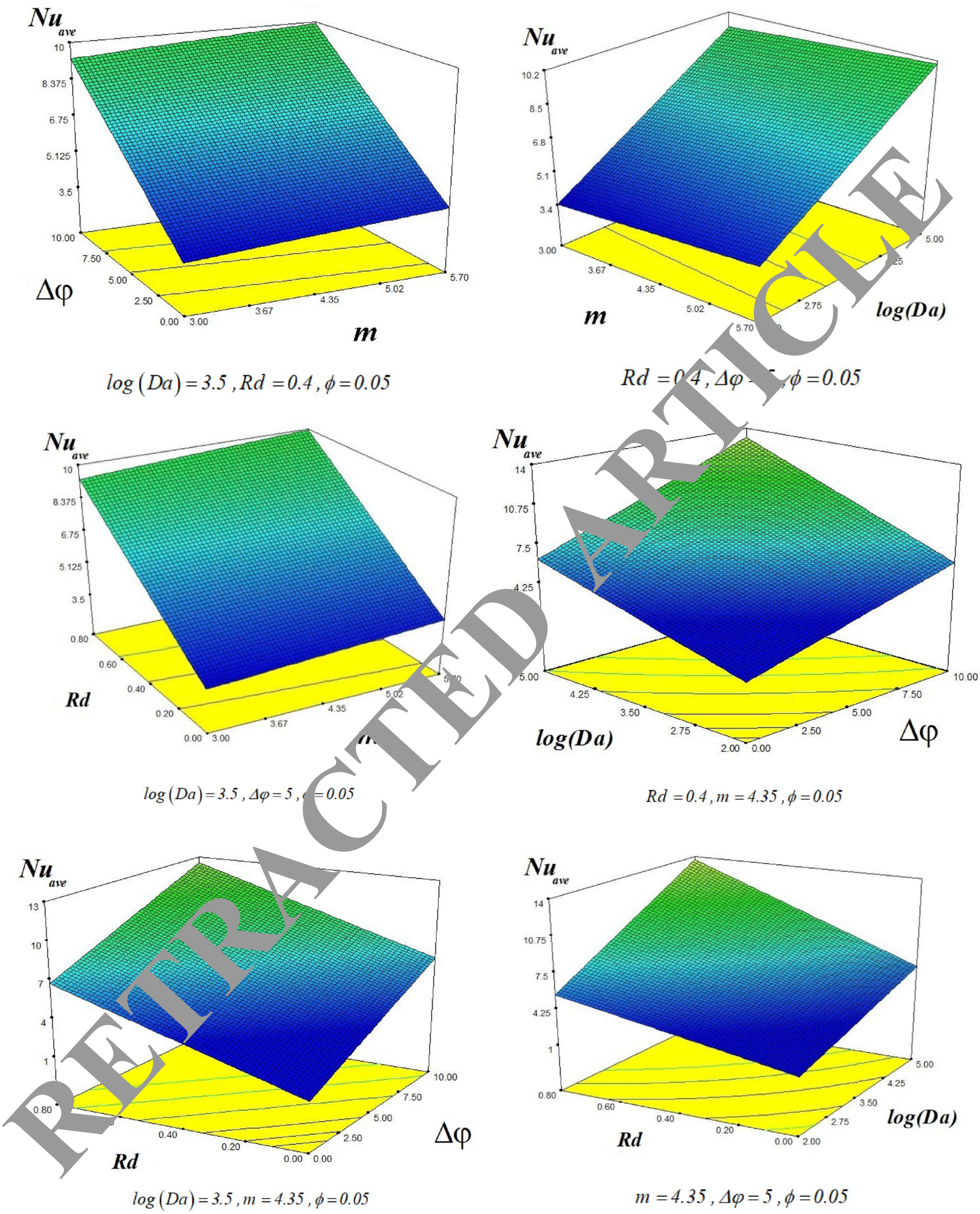


Fig. 8 Calculating Nu for different variables

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Declarations

Conflict of interest Not declared.

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