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NATURAL CONVECTION HEAT TRANSFER INSIDE AN INCLINED SQUARE ENCLOSURE FILLED WITH AL_2O_3 NANOFLUID IN PRESENCE OF PAIR OF DISCRETE HEAT FLUX SOURCES IN BOTTOM WALL

HAYDER KRAIDI RASHID NASRAWI

Department of Mechanics, Babylon University, College of Engineering, Babylon, Iraq

ABSTRACT

The significant of suspended nanoparticle in fluid is the enhancement of heat transfer rate and fluid flow. The effect of the nanoparticle Al_2O_3 on the thermal properties and then heat transfer rate of the base fluid (water) that filled square enclosure cavity with presence of pair of discrete heat flux sources in bottom wall was numerically investigated. Also, the inclination angle was varied over the range of (0^o-60^o) in order to predict the sensitive of the enclose cavity in point of view heat transfer rate and nanofluid flow. Moreover, the relations between angles of inclination and Rayleigh number in conventional fluid are presented. However, the Rayleigh number range that was used in current work is (10^3-10^6). The influence of nanoparticle volume fraction on streamline and temperature distribution contour at different inclination angle with Rayleigh number equal to 10^6 is illustrated. The results show that the heat transfer enhancement increase with increase Rayleigh number. Besides, the increases in concentration of volume fraction at certain inclination angle and with Rayleigh number equal to 10^6 will reduce strength of the streamline function. Finally, the obtained results show that the new proposal by presented pair of discrete heat flux sources in bottom wall of cavity that filled with nanofluid is very benefit for improving the heat transfer rate and fluid flow.

KEYWORDS: Square Cavity, Nanofluid, Al_2O_3, Isoflux, Inclination Angle, Natural Convection

Nomenclature

Cp specific heat, J/ kg K g acceleration of gravity, m/ s h heat transfer coefficient, W/ m^2 K k thermal conductivity, W/ m K L enclosure length m Nu Nusselt number P dimensionless pressure p pressure, N/ m^2 Pr Prandtl number q heat flux, W / m^2 Ra Rayleigh number Ri Richardson number T dimensional temperature, K u, v dimensional velocities components in x and y direction, m/ s U, V dimensionless velocities components in X and Y direction x, y dimensional Cartesian coordinates, m X, Y dimensionless Cartesian coordinates	**Greek symbols** α thermal diffusivity, m^2/s β thermal expansion coefficient, 1/K δ angle of inclination deg. ε diffusivity θ dimensionless temperature μ dynamic viscosity, kg /m s ν kinematic viscosity, m^2/s ρ density, kg / m^3 Φ volume fraction of the nanoparticles % ψ stream function, m^2 /s **Subscripts** c cold f fluid nf nanofluid p particle

INTRODUCTION

The nanofluid technology presented very important modern novel engineering applications by enhancement fluid heat transfer properties. The nanoparticles that possess high thermal conductivity compare with the base fluid will increase the thermal efficiency of base fluid like water, oil, diesel, ethylene glycol [1]. Accordingly, the new fluid capability used with more thermal efficiency in many industrial and engineering applications. Many types of nanoparticle are used to prepare the nanofluid like Cu, CuO, TiO_2, Ag and Al_2O_3 (alumina), where, the alumina is used in this work. The alumina-based nanofluids are important, because it can be used in numerous applications involving heat transfer [1]. The Al_2O_3 nanoparticles varied in the range of 13 to 302 nm to prepare nanofluids, and Veeranna Sridhara and Lakshmi Narayan Satapathy [1] observed the enhancement in the thermal conductivity of alumina is 2% to 36%. Consequently, the efforts of many researchers emphasis to provide optimum nanofluid with high heat transfer efficiency. The free convection in cavity with nanofluid that may be used in many modern applications such as electronic equipment, cooling, solar collector, and this matter presented by many researchers for instance, Sivanandam Sivasankaran et al [2] numerically investigated the convective flow and heat transfer behavior of nanofluids with different nanoparticles in a square cavity. The square cavity consists of two insulated horizontal wall and the right vertical wall is cooled at a constant temperature and the left one is heated linearly. For discrete the transport equations, the finite volume method was used and solved using iterative method.

They reported that the volume fraction of nanofluid have directional effect on the heat transfer rate. Also, they observed that the average Nusselt number is strongly dependent on the nanoparticle chosen. Nemati et al [3] studied the nanofluid heat transfers in the cavity. The fluid under their investigation consists of water as based fluid with Cu, CuO or Al_2O_3 as nanoparticles. The investigation of the mixed convection flows utilizing nanofluids in a lid-driven cavity used Lattice Boltzmann Method. Also, they illustrated that the effect of concentration of nanoparticle decrease when Reynolds number increase. Besides, they found that the LBM (Lattice Boltzmann Method) is a suitable approach for simulating nanofluid. Moreover, Ternik and Rudolf [4] examined the heat transfer enhancement of numerous of nanoparticle Au, Al_2O_3 and Tio_2 with water as base fluid to create the nanofluid that filled enclose square cavity. The conditions of the cavity under their investigation are insulation from top and bottom with high temperature on the left side and the right wall is isothermal cooled. The numerical analysis based on two dimensional under natural convection. They found that low Rayleigh number is more benefit to improve the heat transfer rate than high Rayleigh number. While, Ehsan Fattahi et al [5] applied lattice Boltzmann method to study the natural convection flows capability nanofluids in a square cavity. They used Al_2O_3 and Cu as nanoparticle. Also, they investigated and calculated many parameters like viscosity and thermal conductivity of nanofluid. They found that the average Nusselt number increases by increasing solid volume fraction for both nanofluids. Also, they reported that the effects of solid volume fraction for Cu are stronger than Al_2O_3. Later, Ali Akbar Abbasian Arani et al [6] presented very well numerical solution to investigate the free convection fluid flow and heat transfer in a square cavity filled with Cu-water nanofluid at six different arrangements. These arrangements depend on the position of heat sink.

The main conditions were heat source on its bottom wall as well as two heat sinks on its vertical side walls. They reported that the average Nusselt number of the heat source increases with increase in the Rayleigh number and the volume fraction of the nanoparticles. Besides, they presented and compared their results with the works of other many researchers that deals with nanofluid in cavity application. Eiyad Abu-Nada and Hakan F. Oztop [7] studied the effect of inclination angle and used this angle as a control parameter for flow and heat transfer rate in a two-dimensional enclosure filled with Cu-nanofluid with inclination angles starting from 0^o until 120^o. There is no heating in their works but, the two horizontal walls of the cavity are adiabatic in order to present the effect of the different isothermal temperature that the vertical walls have different temperature. They observed that the Inclination angle can be used as control parameter for nanofluid filled enclosure. Moreover, they illustrated that the Nusselt number is very clear at low volume Fraction. Later, Alinia et al [8] presented mixed convection of a nanofluid with SiO_2 as nanoparticle with different concentration and water as pure fluid. The square cavity under analyze consist of two vertical walls where the left wall is heated and the right wall is cooled at constant temperatures and the other horizontal walls are insulated which represent the moving lids. They reported that addition of nanoparticles enhances heat transfer in the cavity. Also, angle of inclination is more pronounced at higher (Ri) Richardson numbers. Many others researchers deals with nanofluid in cavity like Arefmanesh and Tavakoli [9] presented (MLPG) Meshless local Petrovs-Galerkin method to the 3D natural convection fluid flow and heat transfer in a cubic cavity filled with nanofluids. Mohammad Abu Taher et al [10] used (LBM) Lattice Boltzmann method to study heat transfer and flow of Cu-H2O nanofluid in a square cavity.

They analyzed different non dimensional parameters with internal heat generation (*q*).They reported that The (LBM) is sufficient to simulate buoyancy- driven heat transfer characteristics and flow performance of Cu-H_2O nanofluid in a square cavity. The model of cavity that investigated consists of vertical walls that have different temperatures whereas, the horizontal walls assumed to be adiabatic. Alloui et al (11) presented the numerical solution to simulate natural convection in a shallow rectangular cavity filled with nanofluids. The conditions of enclose are insulated on the two horizontal walls with heated and cooled from the side walls by a uniform heat flux *q*. Three types of nanoparticles were used in their study Cu, Al_2O_3 and TiO_2. They found that for very high Rayleigh numbers, the addition of nanoparticles results in a very small improvement of the heat transfer The most of researchers that presented numerical solution to simulate the behavior of nanofluid filled enclose cavity, using finite-volume method to discrete and then solve the governing equations for different values of Rayleigh numbers and for some other important parameters to be calculated. Nor Azwadi Che Sidik and Reza Masoomzadeh [12] studied the natural convection of nanofluid in a square cavity using Lattice Boltzmann method.

The nanoparticles CuO and Al_2O_3 with water-base fluid are used to prepare nanofluid. They illustrated from the obtained results that the average Nusselt increase as Rayleigh number ascends. The geometry that is used in this study has hot left wall and cold right one wherease the others are assumed to be adiabatic. On the other hand, Hasib Uddin and Sumon Saha [13] used two-dimensional symmetrical trapezoidal as new shape to study laminar steady state natural convection in a enclosure cavity. The presented matter conditions are, the top wall is adiabatic, and both inclined sidewalls have constant low temperature with an isoflux heat source that provided at the bottom wall. They reported that the effect of inclination angle on convection heat transfer characteristics is much observed, when the inclination angle decrease with increase convection heat transfer characteristics. Aminreza Noghrehabadi and Amin Samimi [14] numerically analyzed the natural convection heat transfer and fluid flow in a square cavity filled with CuO–Water nanofluids. The left vertical wall is maintained at temperature higher than the temperature of the right vertical wall. Whereas, other walls of the enclosures are thermally insulated. They found that natural convection become stronger at higher Rayleigh numbers and with high fluid velocity. Achariya Namprai [15] numerically investigated the natural convection in a two-dimensional square cavity with discrete two source–sink pairs on the vertical side and assumes all walls to be adiabatic without inclination. They observed that the number of eddies in the enclosure cavity refers to the behavior of natural convection heat transfer and related to the arrangement of the sources and sinks.

The aim of this research is to investigate numerically the effect of pair of discrete heat flux sources in bottom wall of cavity filled with Al_2O_3-water as nanofluid on flow and heat transfer. Also, the effect of inclination angle with this situation was analyzed. Accordingly, the efforts devoted on the relation between the Rayleigh number (from 10^3 until 10^6) and the flow stream behavior at different angles of inclination. The influence of the nanoparticle volume fraction on streamline at different angles of inclination was predicted. Besides, the isotherm contour behavior with nanoparticle concentration and different Rayleigh number was presented. On the other hand, the comparison between the average Nusselt number of the present search and Benchmark solution [15] was done. Validation of the results satisfy by matched the present results with that of Eiyad Abu-Nada and Hakan F. Oztop [7] and Achariya Namprai [15] and with results obtained by Ali Akbar Abbasian Arani et al [6] as that will be shown in the subsequent articles.

CASE STUDY SKETCH

The schematic of the cavity under analyzed can be shown in figure (1). The enclosure cavity filled with nanofluid. The nanofluid consists of water as base fluid and Al_2O_3 as nanoparticle. The Thermo-physical properties of the base fluid (water) and nanoparticles can be shown in Table 1. The vertical walls have the same temperature T_C. The value of T_C is isothermal along vertical walls. Also, the top wall assumed to be thermal insulation. Innovative of this work is the presence of pair of discrete heat flux sources in bottom wall as shown in figure (1). Moreover, the inclination angle δ changes from 0^o until 60^o with increment 15^o.

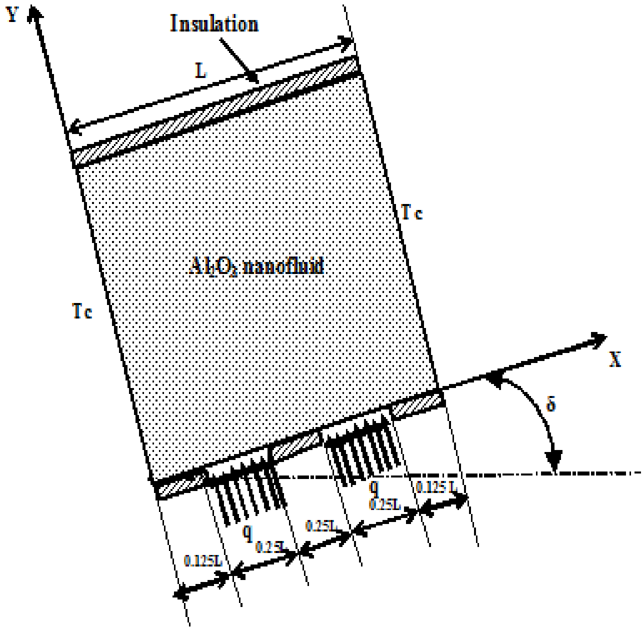

Figure 1: Schematic of the Case Study in the Present Work

Table 1: Thermo-Physical Properties of Base Fluid (Pure Water) and Alumina (Al_2O_3) Nanoparticle [16]

Properties	Pure Water	Alumina (Al_2O_3)
Cp(J/kg.K)	4179	765
K (W/m.K)	0.613	40
ρ (kg/m^3)	997.1	3970
β(1/K)×10^5	21	0.85

GOVERNING EQUATIONS

To convert the governing equation to dimensionless form, the parameters [6], [7] & [11]

$$X=\frac{x}{L},\ \ Y=\frac{y}{L},U=\frac{uL}{\alpha_f},\qquad V=\frac{vL}{\alpha_f},\ \ P=\frac{pL^2}{\rho_{nf}\alpha_f^2},\theta=\frac{T-T_c}{\Delta T},\Delta T=\frac{q\ \ L}{k_f},Ra=\frac{g\beta_f L^3\Delta T}{\nu_f\alpha_f},Pr=\frac{\nu_f}{\alpha_f}$$

Are used to change the general equations, continuity, momentum and energy equations. See references [6], [7], [11] and [16].

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\mu_{nf}}{\rho_{nf}\alpha_f}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra\,Pr\,\sin(\delta) \tag{2}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{\mu_{nf}}{\rho_{nf}\alpha_f}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra\,Pr\cos(\delta) \tag{3}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

Where, the equations 1, 2, 3 and 4 represent the final dimensionless equations.

The density of nanofluid can be given by equation [6], [7] & [11]

$$\rho_{nf}=(1-\Phi)\,\rho_f+\Phi\,\rho_p$$

The governing equation of the thermal expansion coefficient for nanofluid is [6], [7] & [11]

$$(\rho\beta)_{nf}=(1-\Phi)(\rho\beta)_f+\Phi(\rho\beta)_p$$

After assuming spherical nanoparticles according Maxwell [6], the effective thermal conductivity can be given by [6] & [7]

$$k_{nf}=k_f\frac{(k_p+2k_f)-2\Phi(k_f-k_p)}{(k_p+2k_f)+\Phi(k_f-k_p)}$$

The heat capacity of nanofluid is [6]&[7]

$$(\rho C_p)_{nf}=(1-\Phi)(\rho C_p)_f+\Phi(\rho C_p)_p$$

Thermal diffusivity equation for nanofluid is [6], [7] & [11]

$$\propto_{nf}=\frac{k_{nf}}{(\rho C_p)_{nf}}$$

The Brinkman's model (Brinkman, 1952): [6], [7] & [11]

$$\mu_{nf}=\frac{\mu_f}{(1-\Phi)^{2.5}}$$

The local Nusselt number on the heat sources can be defined as follows [6], [11], [15] & [17]:

$$Nu=\frac{hL}{k_f}$$

Where, h is the heat transfer coefficient: [6], [7] & [11]

$$h=\frac{q}{T_s-T_c}$$

Rearranging the local Nusselt number by using the temperature dimensionless, yields: [7] & [11]

$$\mathrm{Nu} = \frac{1}{\theta|_{\text{heat source wall}}} \tag{5}$$

The average Nusselt number $(\overline{\mathrm{Nu}})$ is determined by integration local Nusselt number along the heat source [11] & [17].

$$\overline{\mathrm{Nu}} = \frac{\int_{\text{along heat source}} \mathrm{Nu}\, dX}{\int_{\text{along heat source}} dX} \tag{6}$$

Assumptions

To get a suitable solution for the issue under analyzing the following assumptions was made.

- Spherical nanoparticles of Al_2O_3.
- The flow is laminar and incompressible.
- Newtonian fluid.
- Two source at bottom with equal interval from cavity bottom ends and between each other.
- The vertical walls temperatures are coincides and isothermal along each wall.
- The vertical walls represent the sink.
- The top wall is adiabatic.

By above assumptions, the dimensionless governing equations are solved numerically by finite volume method, for more details about numerical solution method see reference [6], [7] and [16]

RESULTS AND DISCUSSIONS

Depends on the literature survey and to the author's knowledge, The innovative of this research is to investigate the effect of the pair of discrete heat flux sources placed at bottom wall of enclosure cavity that filled nanofluid on heat transfer and fluid flow enhancement.

Also, study the inclination angles effect on heat transfer rate by mutually effect with these two sources at the bottom and the different nanoparticle concentration for each angle of inclination. From table 2 the good agreement can be shown clearly between the results of this work and Benchmark solution [16].

In spite of Benchmark solution used Cu-water nanofluid the difference in average Nusselt number is so small. So, the same agreement in results can be seen for maximum dimensionless temperature θ_{max} and maximum values of stream function ψ_{max}. As shown in table 2 the average Nusselt number increase as Rayleigh number increase.

The stream function gives the same behavior to that of Rayleigh number, while, the maximum dimensionless temperature gives opposite effect compare as Rayleigh number augment. However, at Rayleigh number 10^6 the value of average Nusselt number is maximum and nanofluid heat transfer enhancement is very clear.

Table 2: Comparisons of the Present Results with a Benchmark Solution [16] For Natural Convection in a Square Cavity Filled with Cu-Water Nanofluid (Φ =0.1) (ε=0.4), at Base Heat Flux Wall

Ra	$\overline{Nu}_b$		θ_{max}		ψ_{max}	
	Benchmark [16]	Present Work	Benchmark [16]	Present Work	Benchmark [16]	Present Work
10^3	5.45	5.46	0.205	0.204	0.023	0.022
10^4	5.47	5.45	0.205	0.203	0.251	0.249
10^5	7.12	7.19	0.172	0.171	2.988	2.976
10^6	13.8	13.67	0.107	0.107	11.593	11.585

Figure (2) represent the variations of streamlines for different Rayleigh numbers and cavity inclination angles at nanoparticle volume fraction (Φ) = 0. Where, the Rayleigh numbers change from 10^3 until 10^6 and cavity inclination angles start from 0^o and increment 15^o until reach 60^o. As shown in this figure the new addition to the previous literature by discrete the heat source at the bottom has a clear effect on the efficiency of heat transfer rate and laminar fluid flow. As shown in figure (2), pair of eddies will form with symmetrical shape and opposite streamlines direction at inclination angle equal to zero. The central cell for both eddies have ellipse shape. The pair discrete heat source is motivating these vortices to generate. Also, the absolute values of streamlines increase as the Rayleigh number increase. The augment in inclination angle at low Rayleigh number will increase the size of the left eddy compare with the right one as well as the centre cell shape convert from ellipse to circle shape. Moreover, for each angles of inclination the left eddy will be bigger as the Rayleigh number approach to 10^3 than the Rayleigh number approach to 10^6. The inclination angle 60^o will produce huge vortex at cavity center for all Rayleigh number. Beside, the central cell has circular shape at $Ra=10^3$ and gradually change to ellipse shape at $Ra=10^6$. The results give very good agreement by compared with results obtained by Ali Akbar Abbasian Arani et al [6] and with Eiyad Abu-Nada and Hakan F. Oztop [7] especially at flush situation of the cavity. Also, for more validate the results compare with Achariya Namprai [15]. Depends on figure (2), the effect of pair of discrete heat flux source at bottom of wall can be pronounced from the new stratification starting appear at middle of the bottom wall, especially at Rayleigh number 10^6 with angle of inclination 60^o. The influence of the pair discrete heat source at cavity bottom wall on heat transfer contribution can be observed in figure (3). Where, the figure (3) demonstrated the variation of isotherm contours for the same values of Rayleigh number and inclination angles to that of figure (2). The motivation of the pair of discrete of heat flux source at the bottom wall of enclose cavity on isotherm distribution is very clear. In all results that shown in figure (3) the vicinity region to the discrete heat source has high intensity of isotherm lines and then the isotherm lines dispersed. Figure (3) gives the same results that shown in figure (2) because the uniform distribution of the isotherm that occurs at the inclination angle 60^o with the Rayleigh number 10^3.

The main conclusions from figures (1) and (2) are the fact that the velocity of system increases when the energy transfer increase and then the isotherm temperature distribution tends to be uniform. On the other hand, the influence of the Al_2O_3 nanoparticle volume fraction concentration with pair of discrete heat flux source at bottom of wall of enclose cavity with different inclination angle on streamlines contours at Rayleigh number 10^6 is demonstrated in figure (4). Also, the figure (4) indicated the novel proposal by insert pair of discrete heat flux source at bottom of wall of enclose cavity is a convenient way to control and improve the heat transfer rate and fluid flow of nanofluid. From figure (4), at any inclination angle, the increment in the concentration of nanoparticle will reduce the absolute value of stream function and then the streamlines strength will reduce too. Also, from figure (4) the left vortex at any inclination angle become greater than the right one, whereas the cavity core shape change from ellipse to circle as the volume fraction of nanoparticle increase. However, the inclination angles 60^o represent the best inclination angle, since the strength of eddy is huge compare with other shapes at another inclination angles. Also, the middle zone of cavity tries to be circular shape as the volume fraction of nanofluid increase. The effect of pair of discrete of heat flux source on the bottom wall of cavity on the streamlines denser is very clear at angle $60^{o.}$ This mean when the angle of inclination increases the benefit of heat transfer increases too.

The obtained results validate by compared with Achariya Namprai [15]. Moreover, the effect of presence of pair of discrete heat flux sources in bottom wall is observed at 0^o angle of inclination in figures (2) and (4) by significant two discrete streamlines eddies gives good agreement to that results of Achariya Namprai [15]. Another conclusion can be obtained from figure (4) by maintained the concentration of nanoparticle volume fraction constant, the ψ_{max} pronounced to be increase with angle of inclination increase. Also, for maintained the angle of inclination constant the the ψ_{max} will reduce as the nanoparticle volume fraction augment. The variation of isotherm for different nanoparticle volume fraction and cavity inclination angles at Rayleigh number $=10^6$ is significant at figure (5). As shown in this figure by maintained the concentration of nanoparticle volume fraction constant, the θ_{max} increase with angle of inclination increase until $\delta=30^o$ then the inclination angle effect will adverse. Also, for maintained the angle of inclination constant the θ_{max} will reduce as the nanoparticle volume fraction augment. Moreover, the isotherm lines denser is clear in the vicinity region to pair of discrete heat flux sources placed at bottom wall of enclose cavity at all angles of inclination. From figure (5) the maximum value of θ_{max} occurs at angle of inclination 30^o with nanoparticle volume fraction equal to 5%.

CONCLUSIONS

The effect of pair of discrete heat flux sources in bottom wall of cavity filled with Al_2O_3-water as nanofluid on flow and heat transfer is analyzed numerically. Also, the effect of inclination angle at different nanoparticle volume fraction at Rayleigh number equal to 10^6 is presented. From obtained results, the heat transfer enhancement is increase as the Rayleigh number increase in pure fluid. The nanoparticle volume fraction will improve the heat transfer rate and produce uniform laminar flow at any inclination angle. The maximum θ_{max} occur at low volume fraction 5% and at inclinations sangle 30^o. The symmetrical on eddy and with circular shape at center zone obtained at 60^o with volume fraction 20%. From results the symmetrical isotherm behavior presented at low inclination angle with low volume fraction. The streamlines and isotherm concentrated near the presence of pair of discrete heat flux sources in bottom wall of cavity.

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APPENDICES

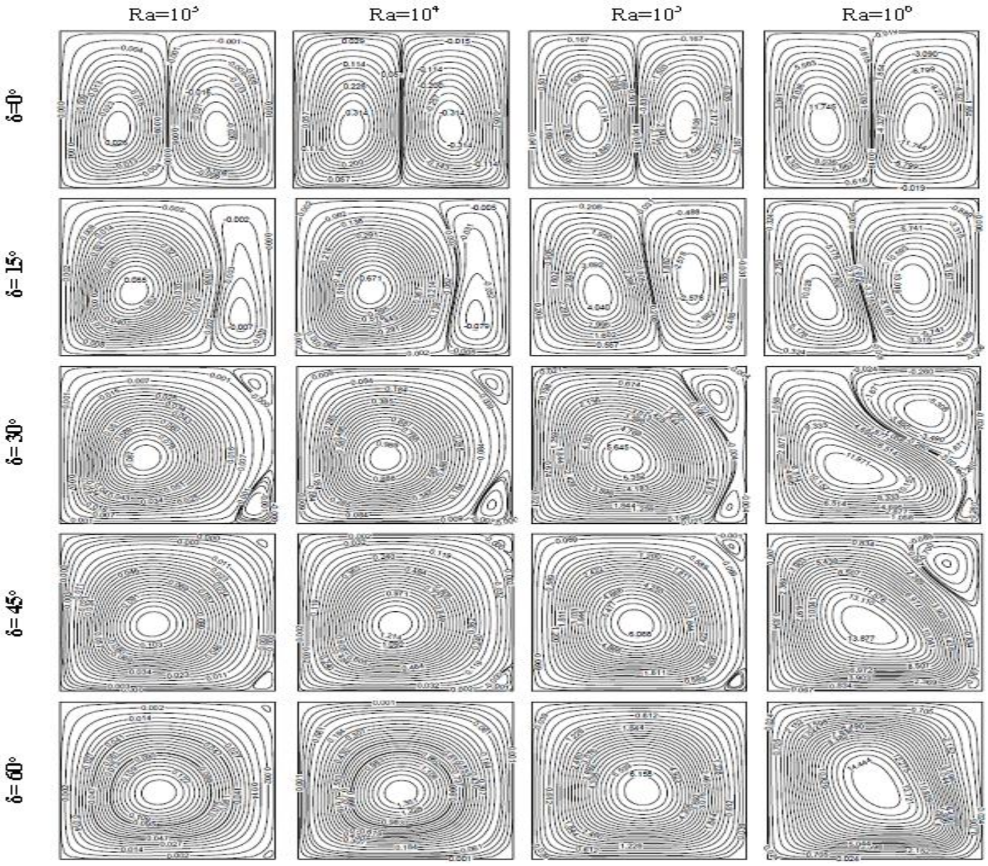

Figure 2: Variations of Streamlines for Different Rayleigh Numbers (Ra) and Cavity Inclination Angles (δ) at Nanoparticle Volume Fraction (Φ) = 0

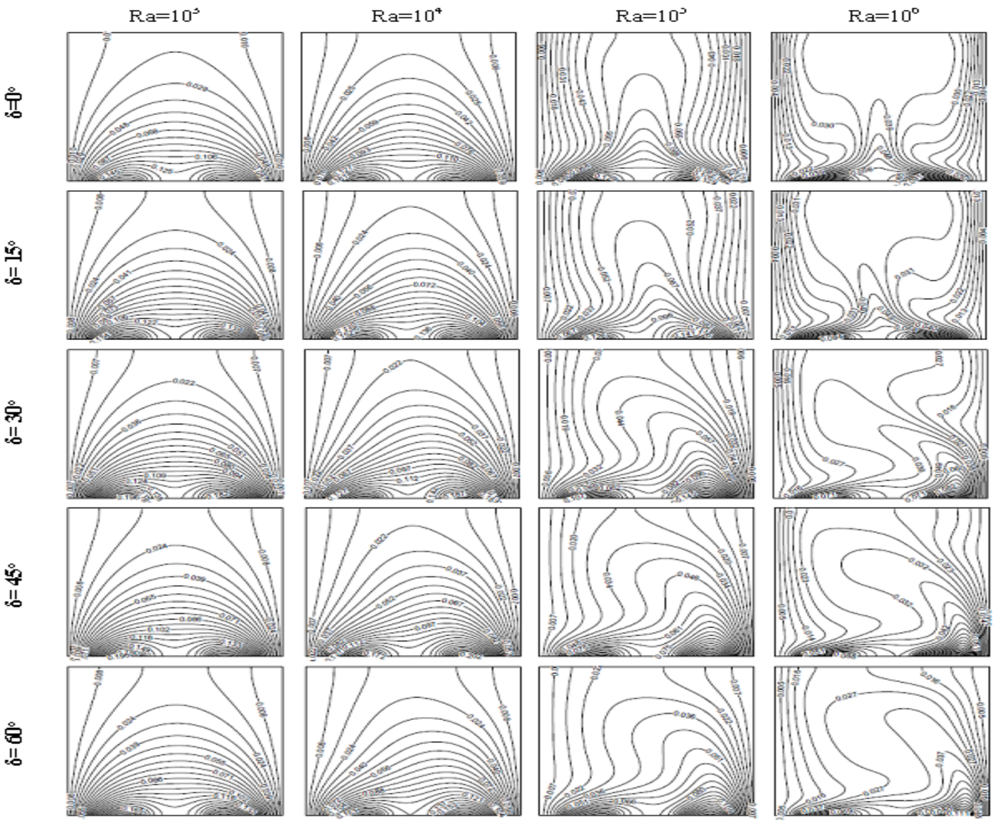

Figure 3: Variations of Isotherms for Different Rayleigh Numbers (Ra) and Cavity Inclination Angles (δ) at Nanoparticle Volume Fraction (Φ) = 0

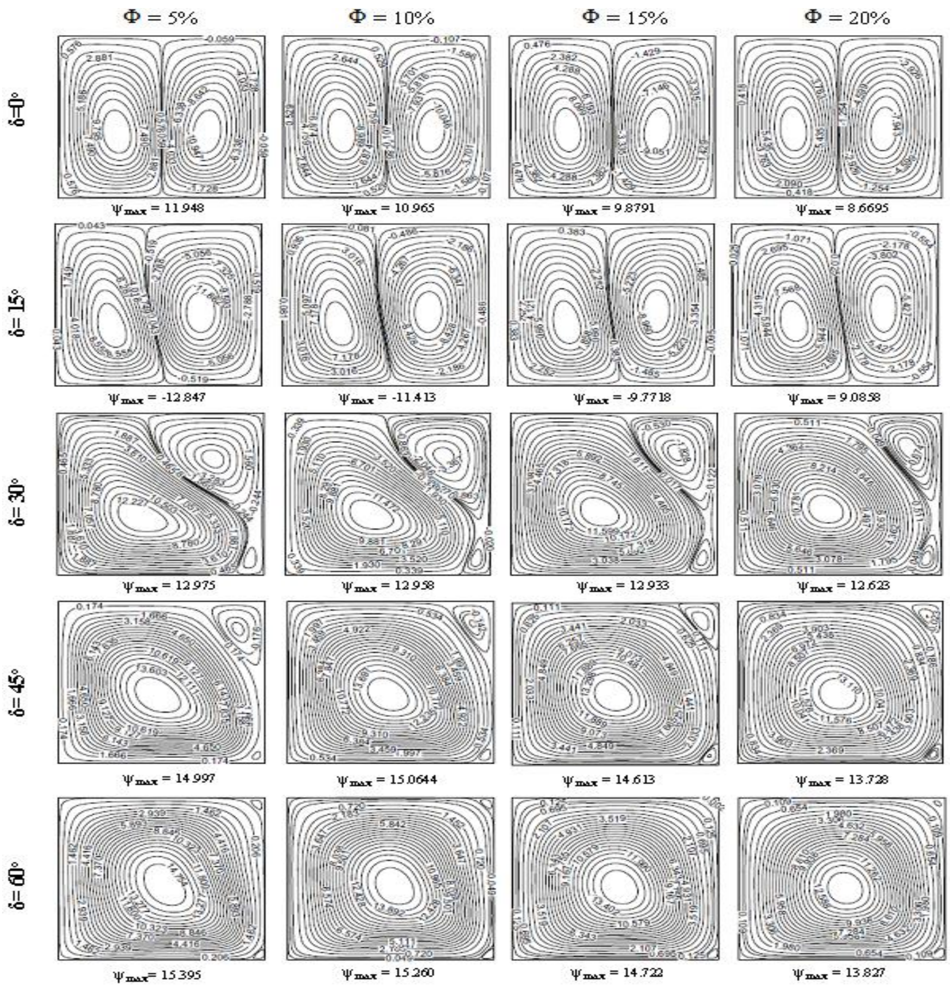

Figure 4: Variations of Streamlines for Different Nanoparticle Volume Fractions (Φ) and Cavity Inclination Angles (δ) at Rayleigh Number (Ra) = 106

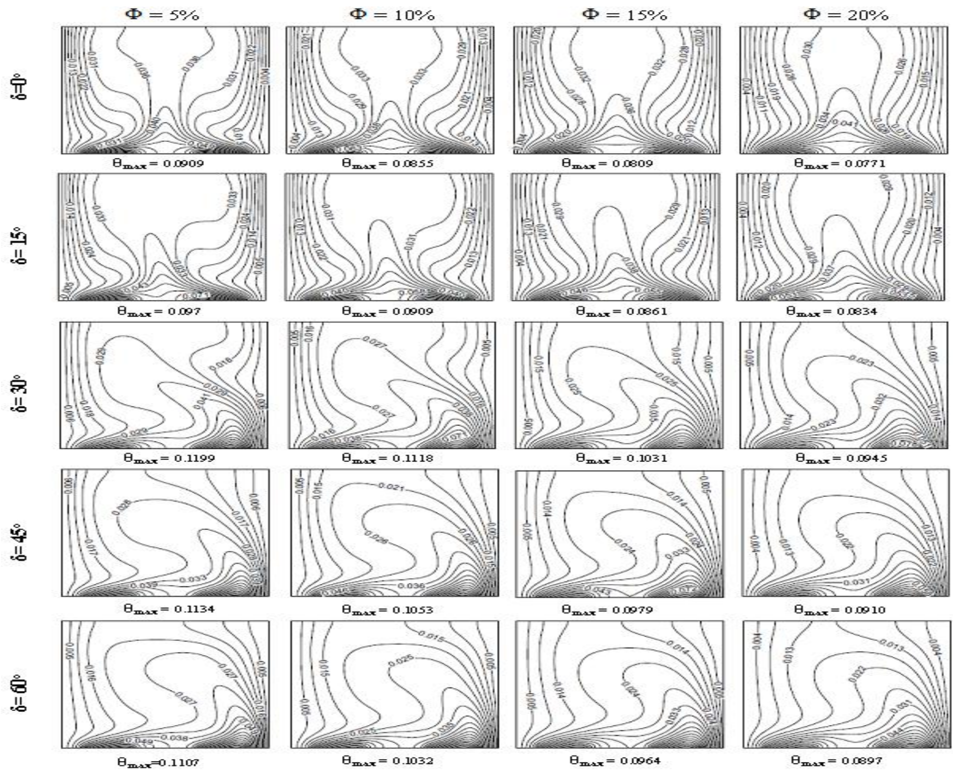

Figure 5: Variations of Isotherms for Different Nanoparticle Volume Fractions (Φ) and Cavity Inclination Angles (δ) at Rayleigh Number (Ra) = 10^6