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Numerical Investigation of Ag-H2O Nanofluid in a Lid Driven Square Cavity with Different Shaped Conducting and Insulating Cylinders Placed at Centre

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ABSTRACT

A numerical analysis is carried out in a lid-driven cavity using silver (Ag)-water nano-fluid by keeping different shape of conducting as well as insulating cylinders at the centre. The cavity is heated isothermally by a heater placed at the bottom. The right and the left walls are in insulated condition and the upper cold wall is moving with some constant speed. The thermal performance of the nanofluid with the cylinder is being analyzed at two Richardson number (Ri=0.01, 10), four percentage volume of Ag nanoparticles (0 %, 2 %, 5 %, 8 %), and a constant value of Grashof and Prandtl number as 10^4 and 6.2 respectively. The two-dimensional, incompressible and steady Navier-Stokes equations are solved using the commercially available Finite-volume based software Fluent. It is analysed that the thermal mixing inside the enclosure is highly dependent on the shape of a solid cylinder. Moreover, the insignificant variation in flow and thermal field is observed with change in the thermal boundary conditions (insulation and conduction) of centrally placed solid cylinder for all the range of Richardson number (Ri). With increase in percentage volume of nanoparticle Nusselt number (Nu) increases whereas Ri has reverse effect on Nu.

1. INTRODUCTION

The fluid such as water, ethylene glycol, mineral oil etc. are often used as heat transporting medium for many industries. It has been experienced that in most of the industrial applications, because of the lower thermal conductivity of the fluids, the power consumption by heat carrying equipments are very high. Consequently, from some decades, the use of nanofluids in the industries have increased by a long way. Nanofluids, which are developed by intermixing the metallic nanoparticles to the base fluids with some surfactants to stabilize the solution greatly enhances the themal conductivity. Nanofluids have applications in chemical industries, thermal power production, microelectronics, chips used in computer circuits etc. To study heat transfer characteristics of nanofluid lid-driven cavity is a benchmarking problem. Many numerical and experimental studies are performed by considering different parameters like cavity size, imposed boundary conditions on the wall, different shapes and sizes of the obstacles placed inside it. Its application is not only limited to scientific world problem like flow over the tubes of the heat exchanger or on the surface of aircraft but also have a wide range of usage in food processing and polymer synthesis industry and to coaters used to produce the high-grade paper and photographic film. Fereidoon et al. [1] in his investigation showed influence of nano-particle volume fraction (ϕ) on heat transfer at a fixed Reynolds Number (Re). The concluding remarks by Akand et al. [2] stated that shape, size and position of cylinders plays a major role on the Nusselt number (Nu) calculation. Daungthongsuk and Wongwises [3] explained about the importance of nano-fluid on heat transfer. Jang and Choi [4] explored a rectangular enclosure with natural convection and came to an end with the statement that nanofluid is more stable compared to the base fluids. Basak et al. [5] inferred that the circulation increases with an increasing Grshof number. Different parameters that governs the flow are explored by Waheed [6]. Muthtamilselvan et al. [7] showed average Nu varies linearly with ϕ. They have also showed that aspect ratio of the cavity has bearings on temperature and flow patterns. Oztop et al. [8] also investigated the problem of lid driven cavity having a circular body at the centre of the cavity. Their result showed that flow field and temperature field inside the cavity is greatly influenced by the presence of the cylinder at the centre. The study investigated by Mina Shahi et al. [9] in an enclosure of square shape which is partially heated from the lower wall explains that to increase Nu at the heating source ϕ value can be increased. MM Billah et al. [10] conducted the study by having a circular body inside the cavity and they showed that dimension of the body plays a significant role on flow field and temperature field. Their study reveals that dimension of the cylinder inside the cavity plays a significant role in heat transfer. TS Cheng [11] looked into the problem of temperature gradient orientation in a cavity and concludes that both Ri and temperature gradient direction affects heat transfer. The numerical investigation was carried out by Sharma et al. [12] considering the cylinder at the centre of the cavity and found that the presence of the cylinder accelerates the heat transfer inside the cavity. It was found that the natural convection significantly affects the flow field at higher Ri and the governing parameter is the size of the heaters. Kumar et al. [13] observed the thermal performance of nanofluid by varying the location of conducting cylinder inside the cavity. Their investigation showed the locations of the cylinder for which maximum heat transfer was obtained. Panigrahi et al. [14] observed the effect of heater located inside the cavity. They also mentioned that importance of heater location in the heat transfer enhancement.

The paper highlights the enhancement in thermal performances by incorporating nanofluid with different shaped cylinders palced inside the cavity, percentage volume of Ag nanoparticles, and Richardson number (Ri).

2. METHODOLOGY

The problem considered in the study is carried out by dispersing silver (Ag) nanoparticles in water (H_2O). The cavity taken is a square shape of length L whose top wall is moving with constant speed and length of each side of the inner body is 0.2 L for square shaped and 0.3L*0.2L for horizontal rectangular cylinder and 0.2L*0.3L for verticle rectangular cylinder. Size of nanoparticles is less than 100 nanometer and the nanofluid behaves as general fluid. Properties of silver nanoparticle and H_2O used for calculation of thermo-physical properties of nanofluid are given in the Table 1.

Table 1. Basic properties of the substrate used in the paper

Material	Base Fluid water	Nanoparticle Silver	Conducting cylinder Titanium
Density (kg.m^{-3})	998.2	10490	4850
Specific heat (J.kg^{-1}.K^{-1})	4182	235	544.25
Thermal conductivity (W.m^{-1}.K^{-1})	0.6	406	7.44

The dimensional steady and incompressible Navier-Stokes equations for different domains are given by:

For Ag-H_2O nanofluid,

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\beta g(T-T_c) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial^2}\right) \tag{4}$$

For solid cylinder of square shape and conducting heat, governing equation of heat conduction is given by-

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=0 \tag{5}$$

Various non-dimensional parameters as well as length, velocity and temperature in non-dimensionalized form used in the investigation are shown below from equation 6 to 16.

$$X=\frac{x}{L} \tag{6}$$

$$Y=\frac{y}{L} \tag{7}$$

$$U=\frac{u}{U_0} \tag{8}$$

$$V=\frac{v}{U_0} \tag{9}$$

$$\theta=\frac{(T-T_c)}{(T_h-T_c)} \tag{10}$$

$$\theta_s=\frac{(T_s-T_c)}{(T_h-T_c)} \tag{11}$$

$$P=\frac{(p+\rho g y)}{\rho {U_0}^2} \tag{12}$$

$$\mathrm{Re}=\frac{\rho U_0 L}{\mu} \tag{13}$$

$$Ri=\frac{Gr}{\mathrm{Re}^2} \tag{14}$$

$$Gr=\frac{g\beta\Delta T L^3}{\upsilon^2} \tag{15}$$

$$\mathrm{Pr}=\frac{\mu C_p}{k} \tag{16}$$

By using the non-dimensional parameters the non-dimensional steady and incompressible Navier-Stokes equations for different domains are given by [2]

For Ag-H_2O nanofluid,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{17}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{18}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ri\theta \tag{19}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{20}$$

For solid cylinder of square shape and conducting heat, governing equation of heat conduction is given by

$$\frac{\partial^2 \theta_s}{\partial X^2}+\frac{\partial^2 \theta_s}{\partial Y^2}=0 \tag{21}$$

Three shapes (rectangle, square and circle) of solid cylinders are placed at the centre of the cavity. The rectangular shape has two different orientation i.e. vertical and horizontal. The analysis is categorized into two parts with respect to the thermal boundary condition of the solid cylinder i.e. insulated and conducting. The cold isothermal lid is moving with a constant horizontal velocity U_o. Two vertical walls are kept stationary and insulated with the stationary bottom wall to be heated isothermally. The schematic diagram of whole domain with different boundary conditions is shown in Figure 1.

If n represents normal direction to any surface then the boundary conditions at the four walls are:
For cavity wall:

$$0 \le X \le 1 \qquad Y = 0 \qquad U=V=0 \qquad \theta = 1 \quad (22)$$

$$0 \le X \le 1 \qquad Y = 1 \qquad U=1,\ V = 0 \qquad \theta = 0 \quad (23)$$

$$X = 0 \quad 0 \le Y \le 1 \qquad U=V=0 \qquad \frac{\partial \theta}{\partial n} = 0 \quad (24)$$

$$X = 1 \quad 0 \le Y \le 1 \qquad U = V = 0 \qquad \frac{\partial \theta}{\partial n} = 0 \quad (25)$$

For conducting solid square cylinder,

$$\left(\frac{\partial \theta}{\partial n}\right)_f = \left(\frac{\partial \theta}{\partial n}\right)_s \quad (26)$$

The governing equations subjected to the above-mentioned boundary conditions are discretized and solved by finite volume method based CFD package FLUENT. QUICK (Quadratic upstream interpolation for convective kinematics) scheme is used for spatial discretization of the convective terms and central difference scheme for diffusive terms. For pressure-velocity coupling SIMPLE (Semi-Implicit method for pressure linked equation) algorithm is used. The convergence criteria are set as 10-10 and 10-12 for continuity and energy equations respectively. The governing equations are non-linear in nature and solved iteratively until the convergence criteria meets for the solutions obtained. The solution variables (e.g., u, v, p etc.) are solved sequentially one after another.

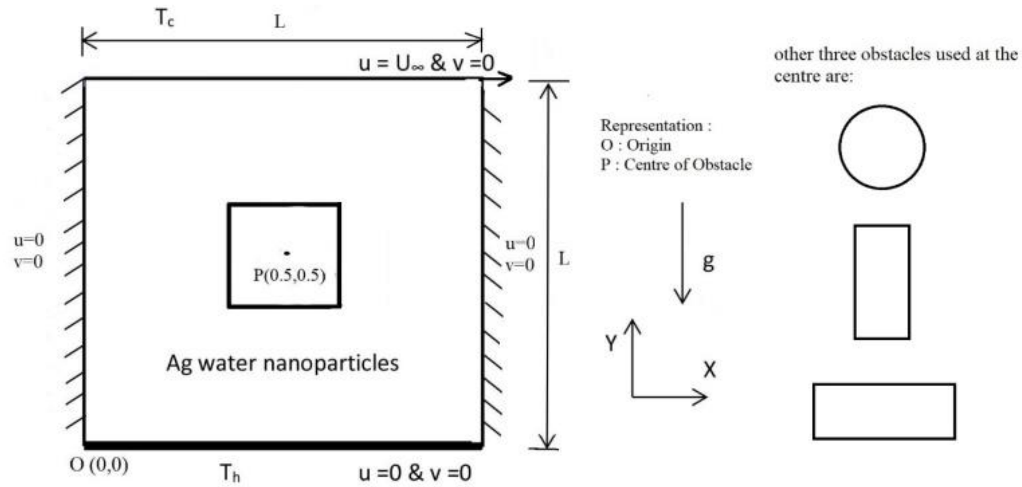


Figure 1. Diagram representing square cavity with square shaped obstacle including boundary conditions

The effective properties of nanofluid are calculated with different empirical relations and equations given by various researchers. Equations 27-29 show the calculation of different thermal and flow properties of nanofluid.

The nanofluid density:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s \quad (27)$$

Heat capacitance is given by

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_s \quad (28)$$

Maxwell-Garnett's [16] approximation model is used to calculate nanofluid effective conductivity. It is considered that Ag nanoparticles present in nanofluid are of spherical type.

$$\frac{k_{eff}}{k_f} = \frac{(k_f + 2k_s) - 2\phi(k_f - k_s)}{(k_f + 2k_s) + \phi(k_f - k_s)} \quad (29)$$

The average value of the Nusselt number is calculated as-

$$\overline{Nu} = \int_0^L \frac{Nu\, dY}{Y}. \quad (30)$$

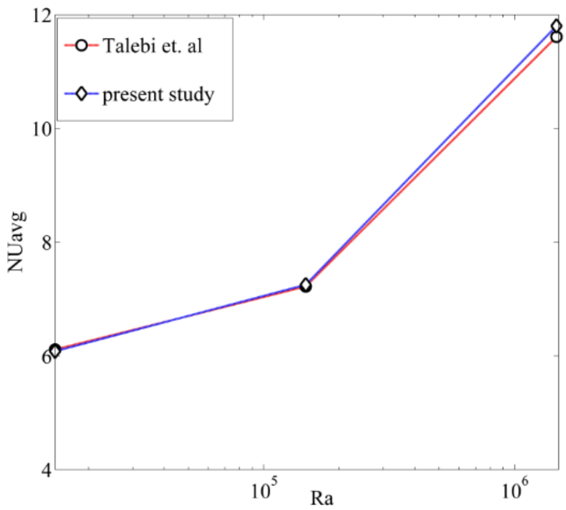


Figure 2. $Nu_{avg.}$ value of present study with Talebi et al. [17]

The adopted numerical model is solved for different Rayleigh number and compared to the results of Talebi et al. [17] with a very promising outcome which is shown in Figure 2. The grid independency is performed at a various number of grids and $Nu_{avg.}$ is calculated at each grid count. The simulations are carried out for Ri=0.1 and Gr=10^4 by considering six types of mesh configuration and accordingly Nu_{avg} is calculated at 31*31, 61*61, 81*81, 101*101, 121*121 and 161*161. It is observed that the variation is nearly 0.0026 % from 121*121 grids. So, further investigations are carried out at 121*121 nodes. Figure 3 shows the detailed mesh structure and the results obtained at these six grid configurations.

Table 2. Variation of averag Nu at different mesh configuration

Mesh configuration	Avg Nu	Variation (%)
31*31	3.151	
61*61	3.262	0.035
81*81	3.353	0.027
101*101	3.421	0.020
121*121	3.440	0.0055
161*161	3.449	0.0026

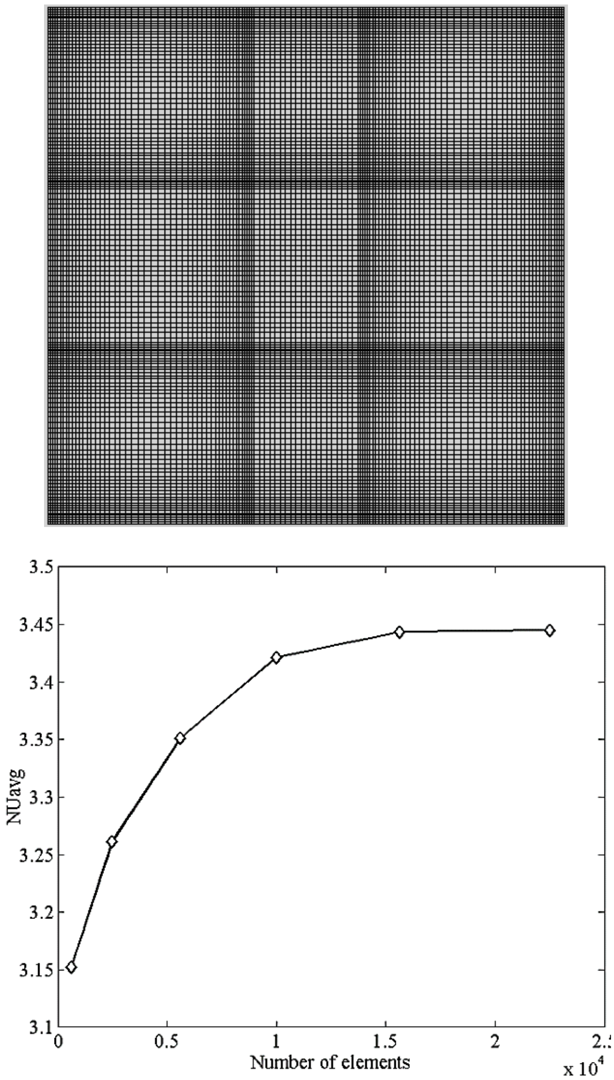


Figure 3. Non-uniform mesh and average Nu with different number of nodes

3. RESULTS AND DISCUSSIONS

The paper discusses thermal performance of nanofluid with variation in Ri, ϕ, and different shapes of conducting cylinder at the centre. Figure 4 to 7 shows streamlines and isotherms for different cases. The circular cylinder is allowing the circulation by providing its edges aligned to for streamline trajectories as shown in Figure 4. The clockwise (CW) flow is induced due to movement of lid towards right direction. At lower Ri the eddies present inside the cavity are only corner eddies. But this scenario changes as the Ri increases and an eddy is detected on the top of the cylinder. This happens due to the vertical dominant velocity since the natural convection dominate. At Ri=10, the isotherm lines heating only the left part of the upper wall. This results in reduction of average Nu at the cold moving wall.

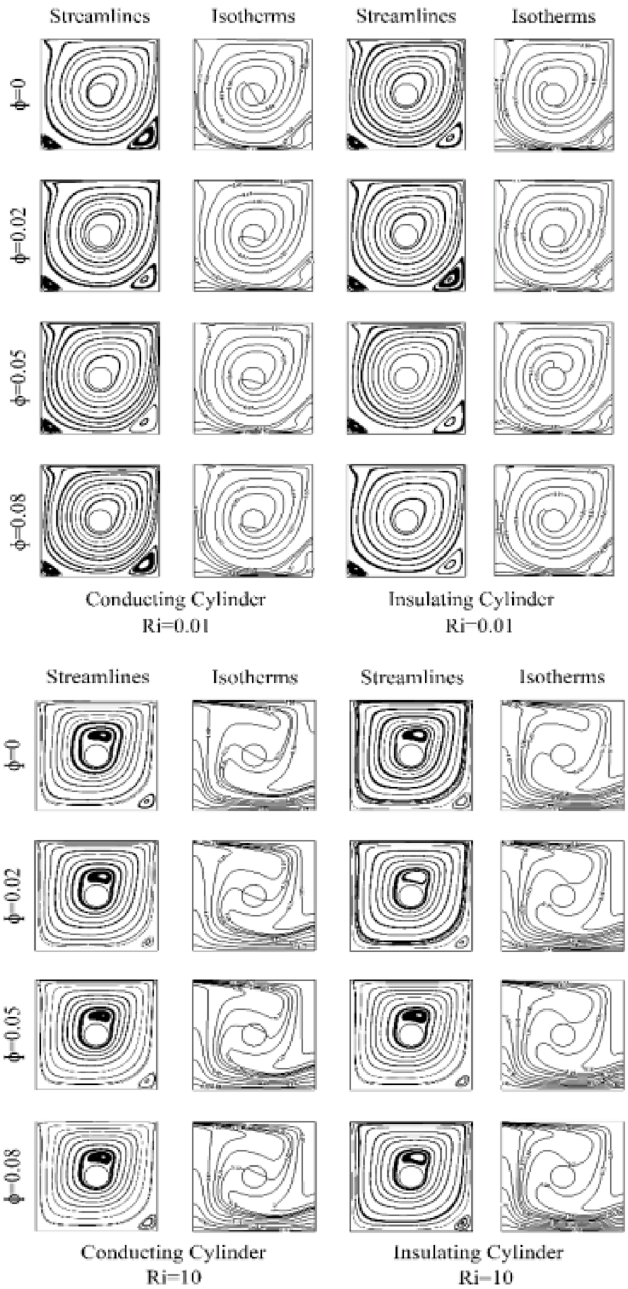


Figure 4. Contour for streamlines and isotherms for circular cylinder

The square cylinder is creating a disturbance to the flow field as shown by streamlines at all Ri in Figure 5. Formation of eddies (corner and at the top of the cylinder) can be seen by all Ri irrespective of ϕ. Similar Isotherms for insulated and conducting cylinders displaying the limited role of thermal properties of the immersed cylinder. As Ri increases the corner eddies get diminished. The isocontours at higher Ri can be seen as uniformly distributed near to the hot wall as natural convection is dominant and heating the upper wall mainly on the left side. At Ri=0.01 the size of the eddies present at the two sides of the bottom wall is bigger as compared to Ri=10. The high velocity of lid at lower Ri causes the flow to separate and thereby bigger eddies are formed at Ri=0.01.

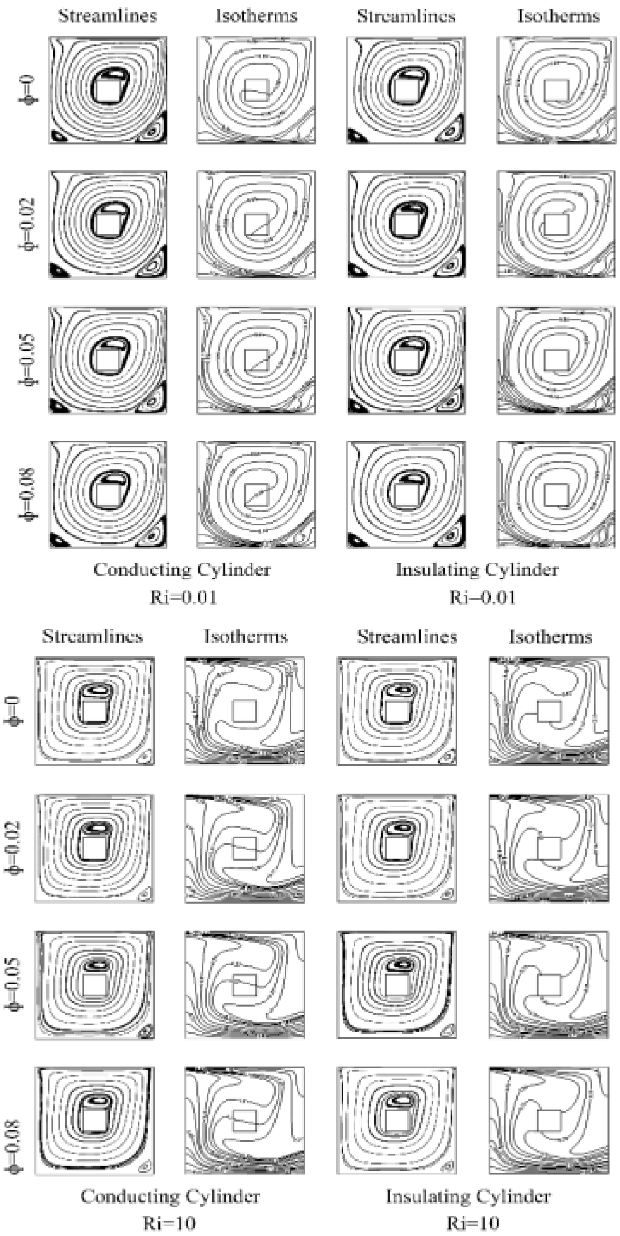


Figure 5. Contour for streamlines and isotherms for square cylinder

The rectangular cylinder is placed in two fashions i.e. horizontal as shown in Figure 6 and vertical, as shown in Figure 7.

At lower Ri, the horizontal rectangular cylinder (HRC) forms the larger sized top eddies as compare to the vertical arrangement. The right corner eddy size for vertical rectangular cylinder (VRC) is more than that of the HRC.

The distorted eddy formation can be observed at lower Ri in VRC case. As Ri increases the Reynolds number decreases and subsequently the vertical flow field in natural convection is highly affected by the obstacle brought against vertical flow field.

The HRC compelling the flow to accelerate in between the cylinder wall and left wall. This contributes towards the formation of large sized eddies at the top of HRC wall. The temperature distribution is hardly affected by the Ri at both insulating and conducting cylinder.

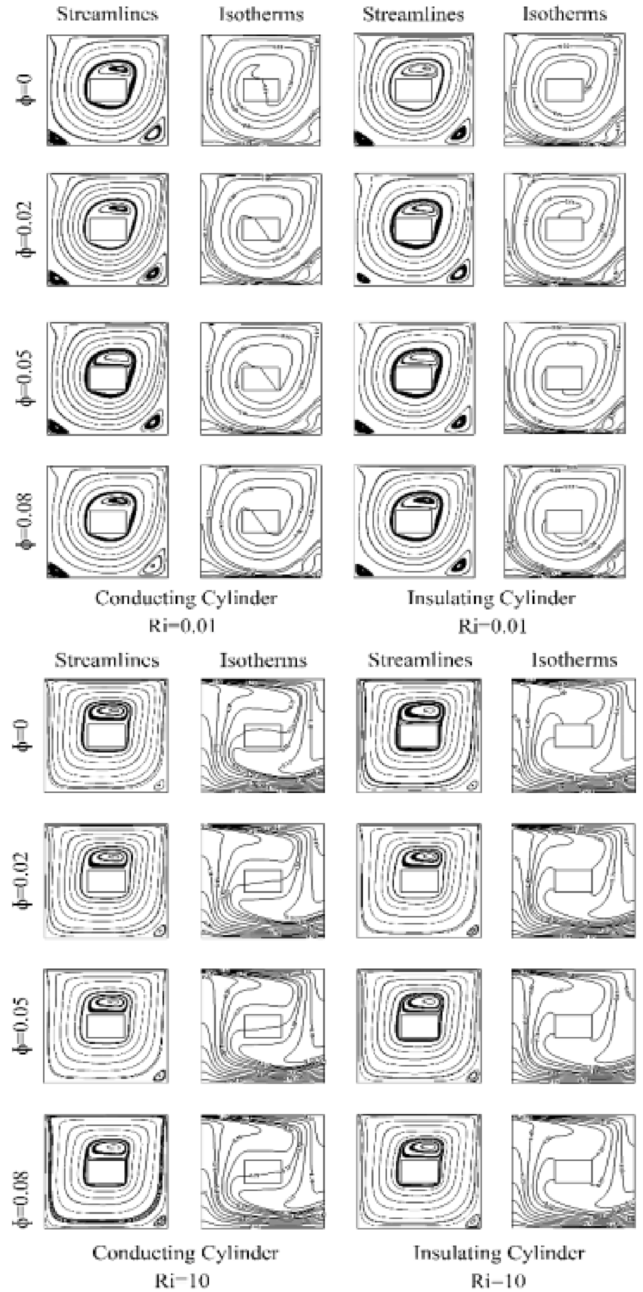


Figure 6. Contour for streamlines and isotherms for horizontal rectangular cylinder

To distinguish the convective heat transfer in any thermal system Nusselt number (Nu) calculation is very important. Figures 8 and 9 represent the average Nu found out at the cold moving wall at two different Ri. The conducting, as well as insulating cylinders, have similar values in all the cases. The flow velocity for all Ri is so high that it is carrying all the heat from the bottom wall away from the cylinders. This shows the insignificance of the thermal properties of cylinders. As ϕ increases Nu increases and Nu decreases as Ri increases.

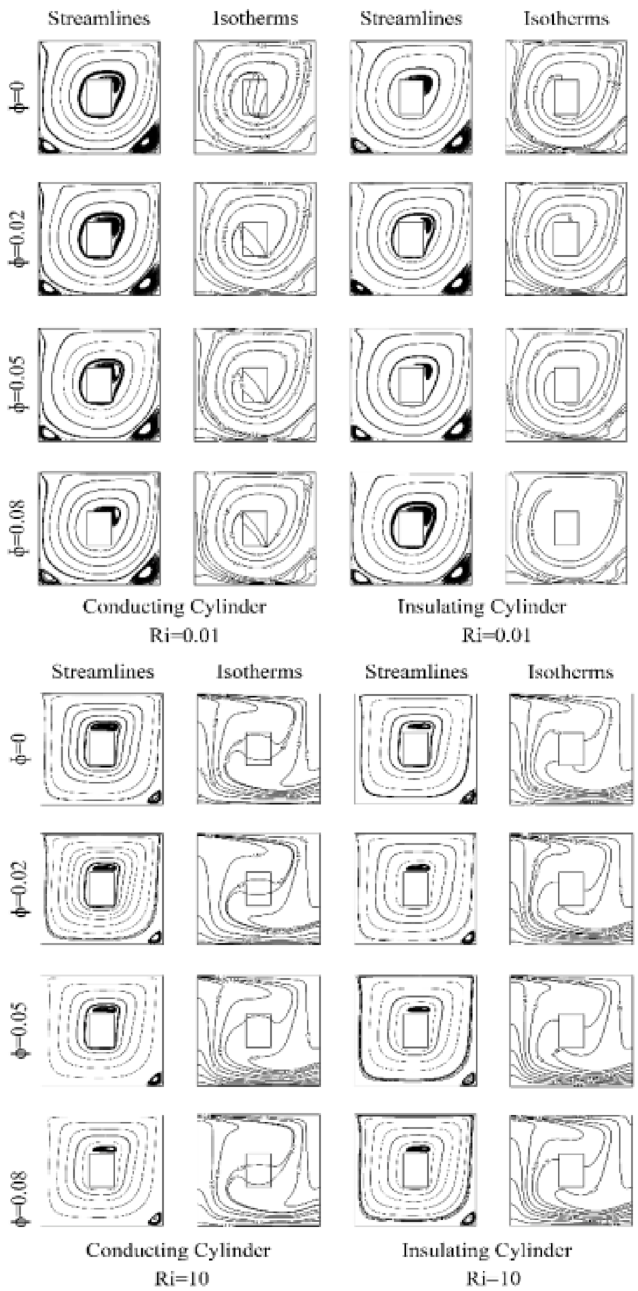
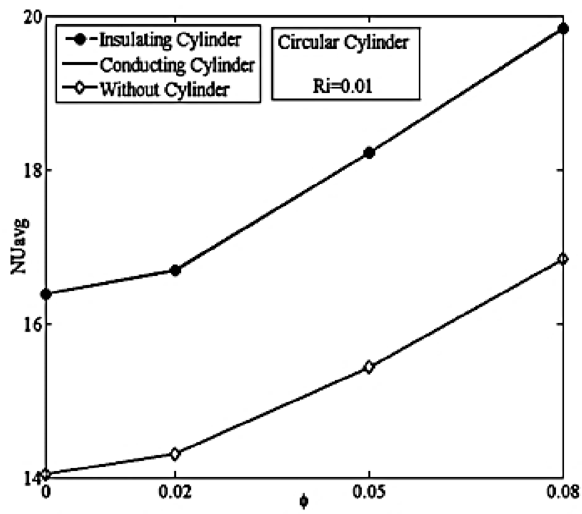
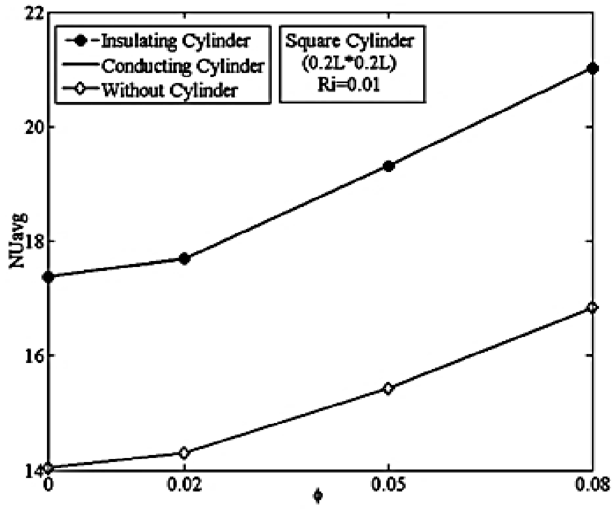
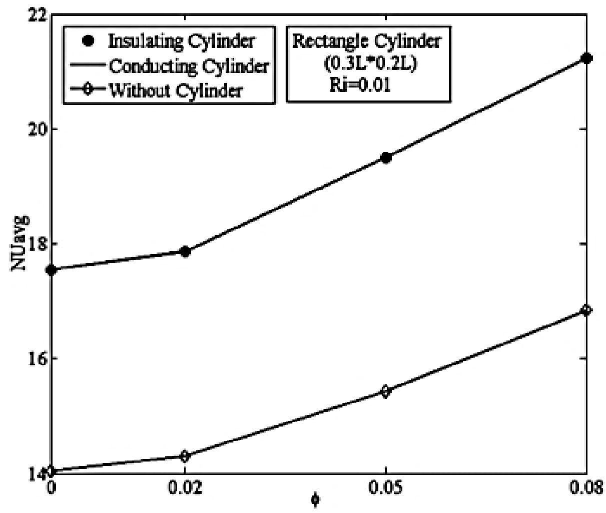


Figure 7. Contour for streamlines and isotherms for vertical rectangular cylinder







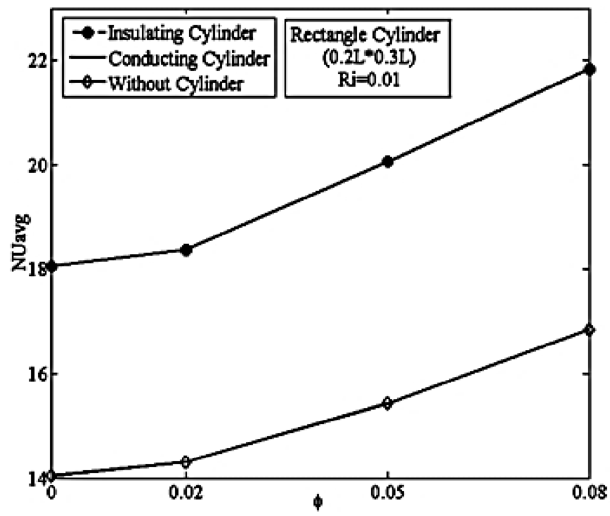


Figure 8. Variation of $Nu_{avg.}$ for the cold moving wall at Ri 0.01

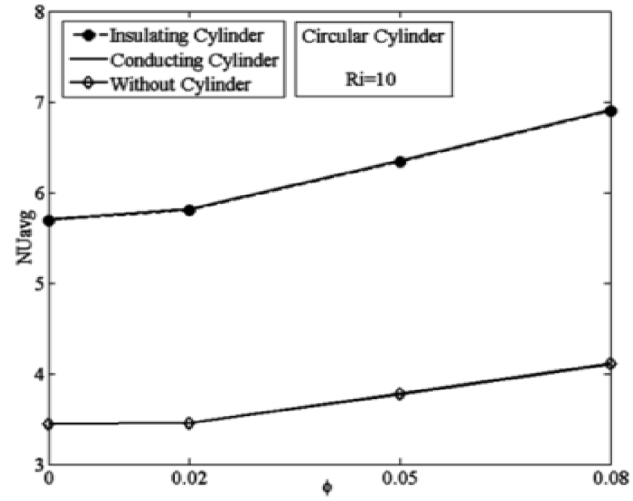
4. CONCLUSIONS

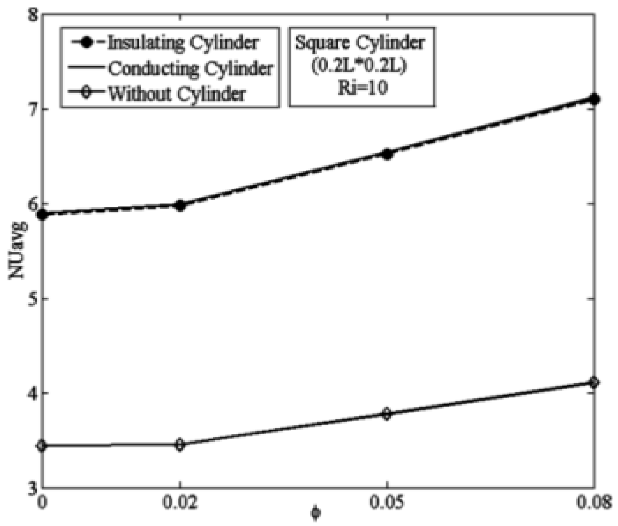
All the cases studied with including cylinders deliver a promising prospect of increasing convection with respect to the cavity without any obstacle inside it. A few concluding remarks can be observed as:

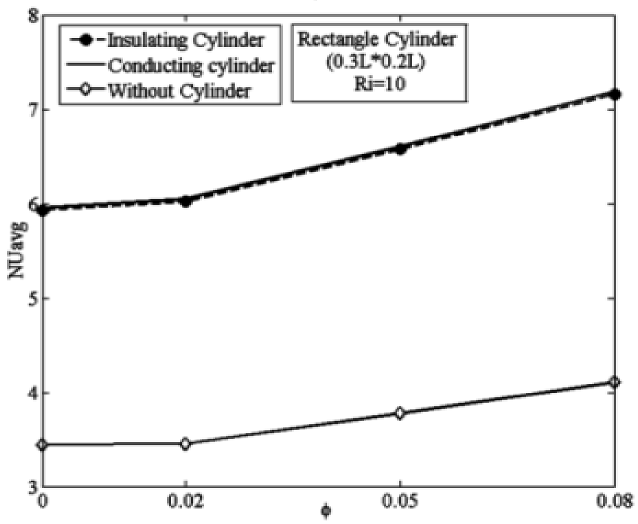
a) As ϕ increases to 2 %, 5 % and 8 % there is increase in Nu by 1.8 %, 11.13 % and 21 % respectively. This result provides an ample opportunity for nano-fluids to be incorporated in various thermal and chemical industries.

b) The effect of thermal properties of a solid cylinder in heat transfer inside the cavity is insignificant at given Ri range as the velocity of the flow field is so high that it takes away the heat away from the cylinder. So it is suggested to use the cylinder made of cheaper materials to just add mixing inside the cavity.

In the case of VRC, the highest Nu is observed for all Ri as it impacts the lower hindrance to the vertical flow field.







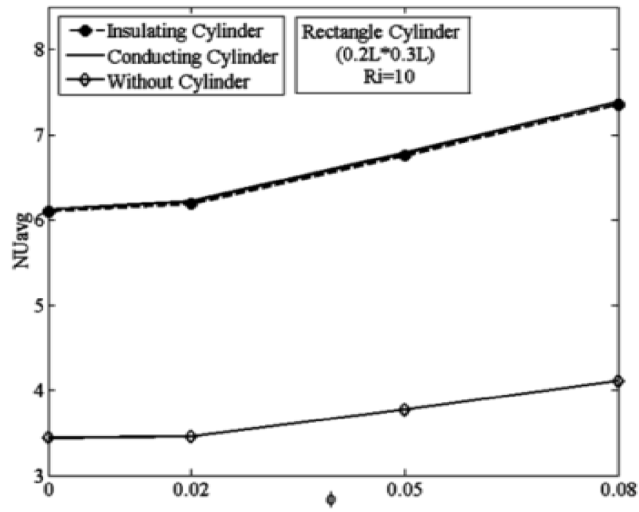


Figure 9. Variation of $Nu_{avg.}$ for the cold moving wall at Ri 10

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NOMENCLATURE

b	Length of heater, m
L	Length of square lid driven cavity, m
h	Heat transfer coefficient, W. m^{-2}. K^{-1}
k	Thermal conductivity, W. m^{-1}. K^{-1}
g	Gravitational acceleration, m. s^{-2}
P	Pressure, N. m^{-2}
T	Temperature, K
C_p	Heat capacitance, J. Kg^{-1}. K^{-1}
u, v	Velocity components, m. s^{-1}
U,V	Dimensionless velocity components
U_0	Lid velocity, m. s^{-1}
x, y	Cartesian coordinates, m
X,Y	Dimensionless cartesian coordinates
Re	Reynold number
Pr	Prandtl number
Gr	Grashof number
Nu	Nusselt number
Ri	Richardson number

Greek symbols

α	Thermal diffusivity, m^2. s^{-1}
β	Thermal expansion coefficient, K^{-1}
θ	Dimensionless temperature
ϕ	Nanoparticles concentration
μ	Dynamic viscosity, Kg. m^{-1}. s^{-1}
ϑ	Kinematic viscosity, m^2. s^{-1}
ρ	Density, Kg. m^{-3}

Subscripts

avg.	Average
c	Cold
h	Hot
f	Base fluid
S	Solid
nf	Nanofluid