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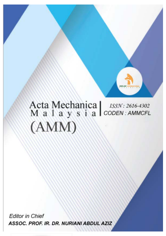

RESEARCH ARTICLE

THE ROLE OF CONCAVE WALLS OF INNER CYLINDER ON NATURAL CONVECTION IN ANNULAR SPACE

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ABSTRACT

The objective of the present research is to provide correct results of the roles of physical and geometrical parameters on the natural convection in an annular space of square cylinders. The physical parameters of the fluid are considered as follow: Prandtl number (0.71, 7.01, 50 and 100) and Rayleigh number (10 power 3, and 10 power 4). However, the studied geometrical modification is based on converting the walls of inner square cylinder from the straight form to the concave form. The work is well done numerically. The predicted results are mainly shown as representative contours of streamlines and isotherms. It was understood that the concave walls of inner cylinder reduces the heat transfer rate that can be useful to use this form in insulating applications instead of straight walls.

KEYWORDS

Square annulus, concave walls, square cylinders, heat transfer, and natural convection.

1. INTRODUCTION

The study of natural convection as a vital mechanism of heat transfer in an enclosed space has witnessed a remarkable attention during the recent decades. This attention is due to its different applications in industry such as: refineries, marine engineering applications, mechanical applications, heat exchangers, nuclear reactors, cooling towers and so on. The main applications of natural convection in annular spaces are divided into two parts: increasing the rate of heat transfer for cooling applications or decreasing the rate for the insulating applications. A group researchers performed a numerical work on the free convection and the forced convection of a circular cylinder which is placed in square cavity (Zhang et al., 2018). The surface of the cylinder is uniformly hot whereas the cavity surfaces are supposed cold. The simulations are done in unsteady state with a laminar regime. A studied the free convection in circular annular space (Ragui et al., 2018). The numerical domain was considered porous.
The main goal of the investigation is to examine the pertinent parameters on the flow inside the enclosed space and predict the evolutions of heat transfer rate. Numerically achieved a study on natural convection inside a circular annular space (Laidoudi, 2020). Indeed, the studied geometry consists of circular cavity with cold wall in which two heated circular cylinders are placed in tandem manner. The work examined the impacts of inner cylinder size, characteristics of the fluid and the buoyancy strength on comportment of the fluid flow and the heat transfer. It was concluded essentially that the augmentation of inner cylinder size reduces the heat transfer which is useful for industrial applications of insulating. In order to improve the heat transfer rate of inner circular cylinder placed which a cold cavity of circular cross-section, some fins were added to the inner cylinder (Nada and Said, 2019). Therefore, the size of the fins and their number on the natural convection was the main goal of the study.

The investigation had a numerical pattern. The impact of buoyancy strength is also studied. The numerical results showed that the presence of fins on the inner cylinder enhances the rate of heat transfer. A studied via a numerical simulation, the nature convection of laminar regime within horizontal cylinders (Laidoudi et al., 2020). The inner cylinder was formed by an orthogonality of two elliptical cylinders whereas; the outer cavity was ordinary kept circular. Numerically carried out a study on the natural convection in circular annular space (Matin and Khan, 2013). The simulations are well done in steady state with a laminar regime. The studied fluid was non-Newtonian which is modeled by the Oswald model. The studied parameters were: the Prandtl number, power-law index and Rayleigh number. The results of the computations proofed that the shear-thinning fluids increase the evacuation of thermal energy whereas, the shear-thinking fluids reduced the rate of evacuated energy.

Therefore, the first sort of fluids is useful for applications of cooling, and the second sort is satisfactory for insulating applications. A study reported a numerical study on natural convection from two circular cylinders placed in tandem arrangement inside a rectangular cavity (Aly, 2017). The domain is porous, and the studied fluid is nanofluid. It was found that the pertinent parameters effect on heat transfer. Simulated the nanofluids in annular space and they concluded that the nanoparticles of solid metal have a possibility to improve the heat transfer (Abu-Nada et al., 2008). A group researchers carried out a numerical work on the natural convection between two cylinders of different temperature (Arbaban and Salimpour, 2015). The goal of this work is increasing the convection heat transfer by adding some radial fins to the inner cylinder and using the nanofluid as thermal convective medium. They found that the number of attached fins play an important role on heat transfer. Examined the eccentricity effect of inner cylinder on the heat transfer (Char et al., 1998).

Achieved an experimental research where he examined the effect of elliptical form of annular space on the thermal buoyancy that was the flow movement source (Eldesouki, 2011). Some researchers used the lattice Boltzmann method to simulate the free convection in viscoplastic fluids

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(Kefayati and Tang, 2018). The considered geometry has circular and elliptical configurations. A scientist achieved a numerical work on the natural convection in concentric annulus, gases are the main fluids used in the annular space (Kumar, 1988). The results provided the effect of pertinent parameters and the radius of the cylinders on the heat transfer. In other hand, researchers proposed a new mathematical method to simulate the natural convection between cylinders (Lamacz et al., 2011). They considered that the inner cylinder having a finite wall thickness (Nasiri et al., 2017). The annular space is this work is assumed to be porous (Sheremet et al., 2015). The nonfluids in annulus where both cylinders are elliptical (Tayebi et al., 2017). A studied the natural convection in annulus of three-dimensions (Wei et al., 1996). An examined the natural convection in unsteady regime (Yoo et al., 2000). The study is in the transient with rotating cylinder (Zhang et al., 1992).

Based on the mentioned works and. It is clear that the heat transfer of natural convection in annular space has two applied purposes: cooling or insulting. Also, the thermal buoyancy strength is controlled by the dimensionless number of Rayleigh. In other hand, the characteristics of fluid that refer to the thermo-physics are defined by the Prandtl number. After global analyses of the literature, it can be seen that no prior results have been reported to the free convection from a square inner cylinder of concave walls. Therefore, the present work tries to give an attempt about that. Indeed, our work studies the roles of concave walls of inner cylinder and thermo-physical parameters on the free convection heat transfer between two concentric cylinders. The rate of heat transfer is evaluated with the average Nusselt number. All simulations are considered in a steady regime. The paper is mainly arranged as: introduction, description of physical model and mathematical formulation, numerical methodology; validation test, results and discussion and conclusion.

2. DESCRIPTION OF PHYSICAL MODEL AND MATHEMATICAL FORMULATIONS

The schematic presentation of present physical mode is illustrated in Figure 1. The studied annular space has two concentric square cylinders. The outer cavity has a cold temperature (T_c) of uniform distribution and inner cylinder is also square with concave walls, and it has a hot uniform temperature (T_h). Both temperatures are assumed to be contestant. The ratio D/H = 0.4, and the concave vale of the walls is given by the ratio c/D = 0.0625. The gap between cylinders of square cross-sections is l = H-D. The fluid used for the numerical simulations is incompressible and Newtonian. The present problem is solved in two-directions (x and y) in a steady regime. The difference between the temperatures generates a buoyancy force along the y-direction. This force is the main source of fluid motion, and it is treated by the Boussinesq approximation. The equations of continuity, momentum and energy are solved numerically to simulate the natural convection inside the studied annular space. The equations are expressed in dimensionless form as:

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

$$\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}=-\frac{\partial p}{\partial x}+Pr\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial vu}{\partial x}+\frac{\partial vv}{\partial y}=-\frac{\partial p}{\partial y}+Pr\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+Ra.Pr.\phi \tag{3}$$

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

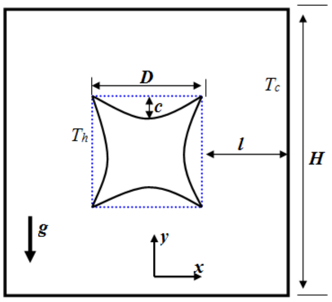


Figure 1: schematic of studied geometry

where these variables *x, y, u, v, p, ϕ, Pr, Ra* are referred to normal and transversal directions, normal velocity, transversal velocity, pressure, temperature, Prandtl number and Rayleigh number respectively. These variables are dimensionless, and they are determined through the following equations:

$$x=\frac{\overline{x}}{l},y=\frac{\overline{y}}{l},u=\frac{\overline{u}l}{\alpha},v=\frac{\overline{v}l}{\alpha},p=\frac{\overline{p}l^2}{\rho\alpha^2},\phi=\frac{T-T_c}{T_h-T_c} \tag{5}$$

$$RR=D/H=0.4,l=H-D \tag{6}$$

$$Ra=\frac{g\beta(T_h-T_c)l^3}{\nu\alpha},Pr=\frac{\nu}{\alpha} \tag{7}$$

where *ρ, ν, α, β* show the thermo-physical characteristics of the fluid. Indeed, they are the density, kinematic viscosity, thermal diffusivity and expansion coefficient respectively. However, *g* is the acceleration gravitation.

The average Nusselt number is the integration of local Nusselt number along the surfaces of the cylinder. The local and average values of Nu are expressed as:

$$Nu_l=\left.\frac{\partial\phi}{\partial n}\right|_{wall} \tag{8}$$

$$Nu=\frac{1}{s}\int_0^s Nu_l ds \tag{9}$$

The dimensionless boundary conditions are imposed on the domain walls as:

On cavity walls:

$$u=0,v=0,\phi=0 \tag{10}$$

On inner cylinder walls:

$$u=0,v=0,\phi=1 \tag{11}$$

3. NUMERICAL METHODOLOGY

The above equations (1) to (4) subjected to the boundary conditions of the equations (10) and (11) are solved numerically using the commercial software of ANSYS-CFX. Figure 2 shows the type of grid that is used for the simulations. The grid consists of small elements which are distributed in non-uniform manner. The concentration of elements is around the inner object. The simulations are considered only when the relative error is less the value 10^{-8} for the continuity and momentum and less than the value 10^{-6} for the energy equation. Furthermore, the accuracy of the grid is proofed through the step of grid independency test. Three grids of different density are generated gradually, and for each grid the value of Nusselt number of the cylinder is calculated. Table 1 collects the values of grid density and the values of *Nu*. It is clear that the variation of *Nu* with grid density is almost negligible. So, it can be determined that the grid 2 is satisfactory for this investigation.

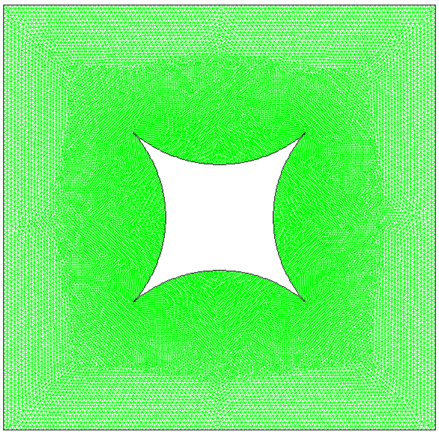


Figure 2: Grid of the computational domain

Table 1: Grid Independency test for *Ra* = 10^4 and *Pr* = 10

Grid	G1 (elements)	G2 (elements)	G3 (elements)
	48260	108078	191970
Nu	2.85093	2.83271	2.83392

4. VALIDATION TEST

This step is added to show the precision of our numerical methodology which involves the governing equations and the boundary conditions. For that reason, we have performed the same investigation and the numerical one of (Matin and Khan, 2013; Kuehn and Goldstein, 1976). Figure 3 collects the present results with the prior results. A good agreement is seen from the preventative figure.

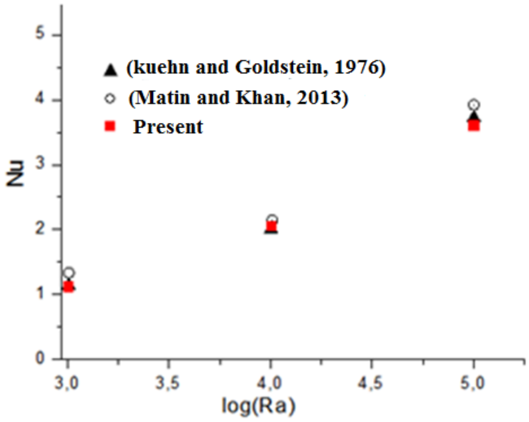
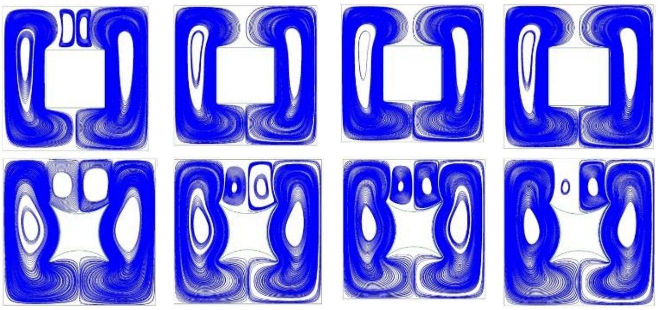


Figure 3: Validation test

5. RESULTS AND DISCUSSION

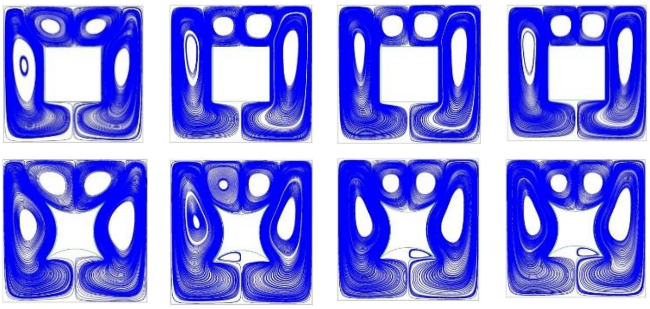
The natural convection in annular space is investigated numerically to show the impacts of pertinent parameters on the fluid motion and the evacuated quantity of thermal energy. The work is accomplished for these studied parameters: Pr = 0.71 to 100 and Ra = 10^3 and 10^4. Also, the effect of geometrical configuration on the thermal energy is also considered. The inner cylinder is considering square cross-section with straight or concave walls. The analyzes of flow and temperature are done by the streamline and isotherm contours. The variations of Nu (average Nusselt number) are plotted versus the all studied parameters.

Figure 4 and 5 show the streamlines in the studied domain with progressive increase in the values of Prandtl and Rayleigh numbers. Indeed, Fig. 4 is for Ra= 10^3, and Fig. 5 is for Ra= 10^4. It is important to clarify that the principal source of fluid motion is the thermal buoyancy force i.e. the fluid layers around the surfaces of inner cylinders become hot and the layers of fluid that are near the outer cavity become cold as consequences, the density of hot zones decreases and the density cold zones decrease, and accordingly the hot zones move up whereas, the cold zones move down. This pattern of fluid movement creates two big symmetric vortices that almost occupy the entire domain. Also, there are two extra loops are seen over the inner object. The extra loops disappear over the inner cylinder of the straight walls only for Ra = 10^3 and Pr = 0.71. Furthermore, for Ra = 10^4 and for Pr = 7.01, 50 and 100 an extra small pair of loops are appeared under the inner cylinder of concave walls. For both studied geometries, it can be remarked that the impact of Pr number becomes constant when Pr > 7.01.



Pr = 0.71 Pr = 7.01 Pr = 50 Pr = 100

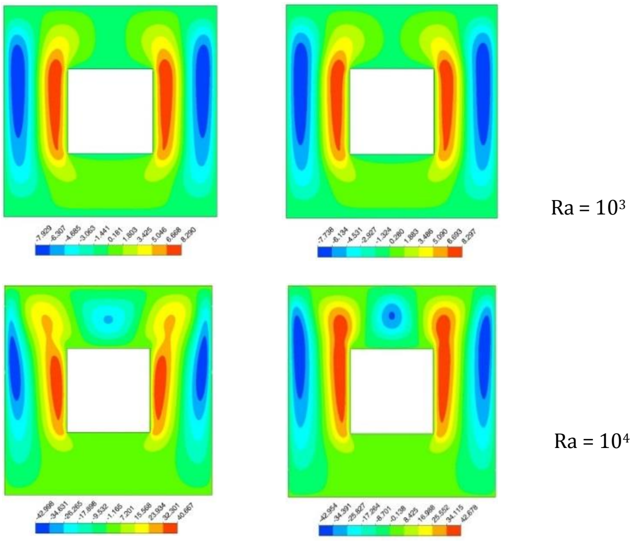
Figure 4: Streamlines in annular space for different Pr at Ra = 10^3



Pr = 0.71 Pr = 7.01 Pr = 50 Pr = 100

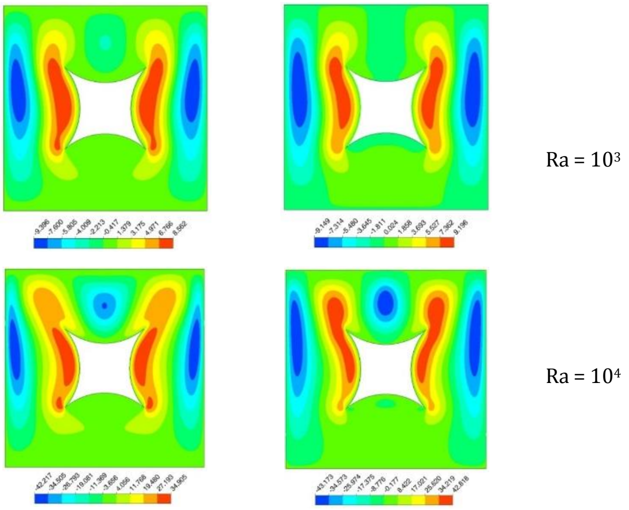
Figure 5: Streamlines in annular space for different Pr at Ra = 10^4

Figure 6 and 7 are depicted to show the dimensionless velocity component (v) along the y-direction. Figure 6 is for the square cylinder of straight walls and figure 7 is for the square cylinder of concave walls. It is clear that the positive value of dimensionless velocity (v) is close to the inner cylinder but the negative value is near the outer cavity. The values of dimensionless velocity are almost constant with changing Pr. In other hand, a significant increase of dimensionless velocity with increase the Rayleigh number. This due to when the value of Ra is increased the force of thermal buoyancy becomes more strength and according the velocity of the flow increases. Furthermore, the concave walls are seen to influence on the dimensionless velocity distributions.



Pr = 0.71 Pr = 7.01

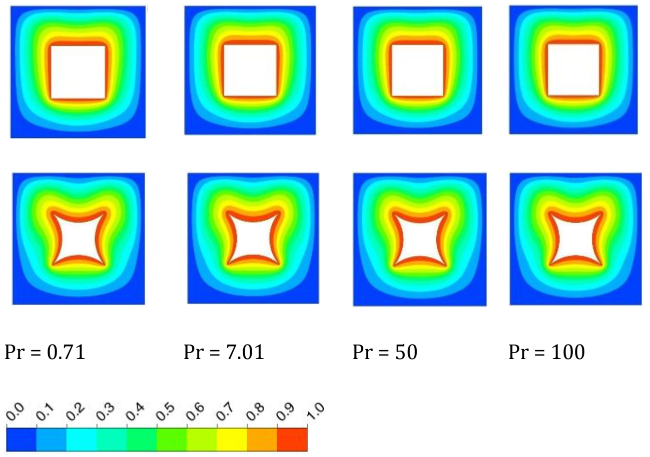
Figure 6: Contours of dimensionless velocity component along the y-direction for the straight walls



Pr = 0.71 Pr = 7.01

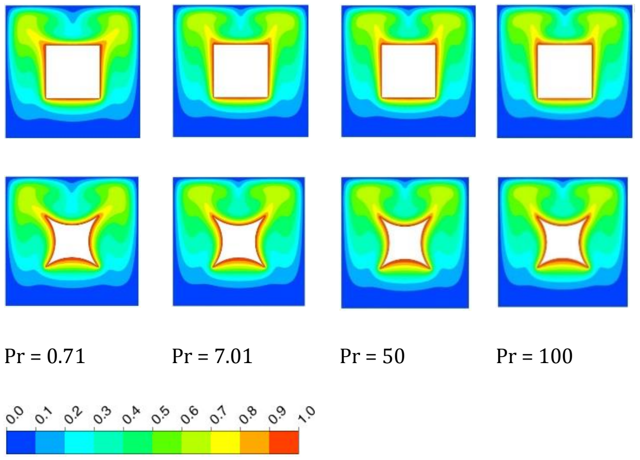
Figure 7: contours of dimensionless velocity component along the y-direction for the straight walls

Figure 8 and 9 show the contours of dimensionless temperature (isotherms) for the studied parameters. Indeed, Fig. 8 is for Ra= 10^3, and Fig. 9 is for Ra= 10^4. It is clear that the highest values of dimensionless temperature start from walls of hot cylinder towards the upward direction. In other hand, the lowest values of dimensionless temperature are seen near the outer cavity toward the downward direction. For all cases the role of Pr is almost constant for all geometries. The isotherms are crowded around the inner cylinder means that the thermal gradient is very important and then the rate of heat transfer is also important. It is shown that the thermal gradient increases with increase Ra number. In other hand. The thermal gradient decreases as we move from the inner cylinder of straight walls to concave walls. Therefore, we can expect that the concave walls reduce the heat transfer rate. Finally, it was concluded that the concave square is important for the insulting application better than the ordinary square cylinder.



Pr = 0.71 Pr = 7.01 Pr = 50 Pr = 100

Figure 8: Isotherms in annular space for different Pr at Ra = 10^3



Pr = 0.71 Pr = 7.01 Pr = 50 Pr = 100

Figure 9: Isotherms in annular space for different Pr at Ra = 10^4

Figure 10 shows the variations on average Nu number as function of Pr and Ra numbers for both studied geometries. It is clear that for both geometries the effect of Prandtl number on values of Nusselt number is almost constant. In other hand, increase in Ra number increase the Nu as consequence it increases heat transfer rate. As it was expected the concave walls decrease the values of Nusselt number. For example, for Pr = 7.01, Nu decreases by 13.8% for Ra = 10^3 and by 11.19% for Ra = 10^4.

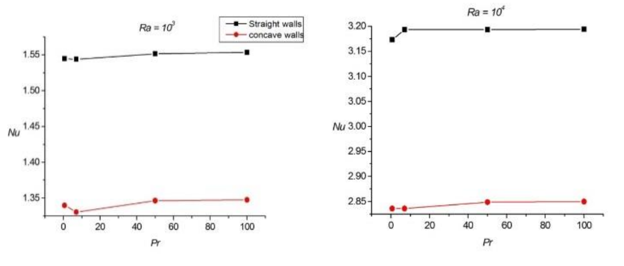


Figure 10: Average Nusselt number on inner cylinder versus Pr and Ra

6. CONCLUSION

The numerical investigations are performed to study the free convection heat transfer inside an annular space. The studied annular space consists of two concentric cylinders of square cross-section. The effects of pertinent parameters as Pr and Ra numbers on the thermal activity are considered. Also, the walls of inner cylinder are considered straight and concave. The numerical results of present simulations let us to determine the following points:

- All obtained contours of streamlines and dimensionless velocity and temperature are seen symmetric hinting that the physical phenomena are perfectly steady.
- The flow in annular space has recirculation patterns.
- The impact of Pr number on hydrodynamic and thermal comportments is almost constant for the studied range of parameters.
- Increase in Ra number increases the flow velocity inside the domain.
- The heat transfer rate increases with increasing Ra number.
- The concave form of cylinder walls decreases the heat transfer rate for example when Pr = 7.01, Nu decreases by13.8% for Ra = 10^3 and by 11.19% for Ra = 10^4.
- The concave form of inner cylinder is more efficient that ordinary square cylinder for insulating application.

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