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Numerical study of natural convection around a square cylinder within a square enclosure for different orientations

Rahul Ryan Savio[1] · Subhani Shaik[1] · Rajendran Senthil Kumar[1]

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Abstract
To attain the goal of sustainable development of resources, a study was conducted around a heated square cylinder placed inside a relatively cooler square enclosure. The temperature difference between the enclosure and cylinder is governed by different Rayleigh numbers (10^4, 10^5 and 10^6). For each case, analysis was done to know how the change in orientation of cylinder about its central axis affects the heat flow and flow characteristics. The problem is analyzed using ANSYS fluent and the plots are built-in Tecplot. The study also hopes to provide necessary analysis on flow characteristics by swotting through the Nusselt number, Skin friction coefficient, and pressure coefficient of each case. To further enrich the study, analysis on its vorticity, velocity magnitude, and drag is done. By comparing a square at the different rotation of 0°, 15°, 30°, 45°, 60°, and 75°, we inferred that 45° angle of rotation provides the most optimum and efficient means of heat transfer higher Rayleigh number. This is caused due to effective formation of the recirculation system around, which is formed due to an increase in velocity and skin friction drag around the cylinder and inside the enclosure.

Keywords Natural convection · Square enclosure · Square cylinder · CFD · Fluid flow

List of symbols

T_h	Temperature of cylinder walls (k)
T_c	Temperature at walls (k)
H	Side of the square enclosure (m)
L	Side of the square cylinder
θ	Rotation angle
Nu	Nusselt number
Ra	Rayleigh number
k	Thermal conductivity $\left(\frac{\mathrm{W}}{\mathrm{K\,m}}\right)$
β	Thermal expansion coefficient (K^{-1})
T	Surface temperature (K)
T_∞	Bulk mean temperature (K)
α	Thermal diffusivity ($\mathrm{m}^2\,\mathrm{s}^{-1}$)
v	Kinetic viscosity ($\mathrm{m}^2\,\mathrm{s}^{-1}$)
h	Convective heat transfer coefficient ($\mathrm{w\,K\,m}^{-2}$)
k	Thermal conductivity ($\mathrm{w\ K\,m}^{-1}$)
C_f	Coefficient of skin friction
τ_w	Shear stress ($\mathrm{N\ m}^{-2}$)
ρ	Density ($\mathrm{kg\ m}^{-3}$)
C_p	Pressure coefficient
p	Static pressure ($\mathrm{N\ m}^{-2}$)
p_∞	Free stream pressure ($\mathrm{N\ m}^{-2}$)
V_∞	Free stream velocity ($\mathrm{m\ s}^{-1}$)
p_o	Stagnation pressure ($\mathrm{N\ m}^{-2}$)
V	Velocity ($\mathrm{m\ s}^{-1}$)

✉ Rajendran Senthil Kumar
senthilr2@srmist.edu.in

[1] Department of Mechanical Engineering, SRM IST, Chennai 603 203, India

Introduction

In the last 50 years, we have seen an exponential rise in consumption in electric and electronic goods, e.g., electronic devices such as bulbs, mobile phones, computers, television, etc., and energy storage devices such as batteries, capacitors, etc. But this rise has led to an exponential growth in worldwide energy consumption. And the inefficient usage of energy has caused drastic climate change in the earth's environment. This is very much evident and can be seen in form of a rise in global temperatures and erratic change in seasons. Hence, there is a need to innovate technologies that are energy efficient and to cut back on losses caused inadvertently due to heat dissipation into the surroundings, e.g., heat loss in refrigeration units and heating up of computers which leads to computational loss of the device. This heat dissipates into the air through means of free or forced convection. Forced convection is a heat transfer mechanism that can be seen in devices like a CPU fan, electric coolers, air conditioners, etc. These devices blow in air to dissipate heat and to cool the system. But forced convection cannot be used when we take into consideration microelectronics elements or delicate devices and places which are inaccessible or enclosed system; for example, in Nuclear Power plants the reaction chambers are enclosed system and heat transfer takes place through means of natural convection. If this was not the case, then radioactive materials may come in contact with the surrounding air and contaminate the facility. Hence, a study was conducted to numerically find out the heat transfer rate through natural convection of air around a heated square cylinder (general shape of the electronic device) kept inside a square enclosure at room temperature. The square shape was chosen as it's the most ubiquitous used shape for microelectronic components. The study is further driven by the fact to understand flow characteristics and working of air around the square cylinder placed inside a square enclosure. Through this research, we try to find the most optimum orientation of a square cylinder for maximum cooling. This is done by comparative study for different orientation of cylinder and how the flow characteristics vary with each rotation.

Based on which we have selected relevant papers that enrich and accentuate the current paper.

Ostrach [1] researched natural convection in square enclosures. This was one of the first papers to formulate a type of problem around the square enclosure and natural convection, and to explain the driving force behind natural convection is having walls at a different temperature or heat flux.

Davis and Jones [2] in their paper did a benchmark study on natural convection in a square enclosure by use of software called FRECON. They mainly compared and compiled data from research papers provided to them by various experts in the field. They tried and tested the accuracy of different methods defined in these papers, as well as the computational aspect of these types of systems and how to simulate it in computers. Shu et al. [3] have studied a system of a square enclosure with a cylinder place at its center using the differential quadrature method. This paper concludes that the DQ method is efficient for solving a system with weak global circulation. The paper is validated by comparing and contrasting data of the present paper against previous papers done on similar systems. Jami et al. [4] researched the behavior of fluid around a conducting cylinder and its isotherm by using the Lattice Boltzmann method and finite-difference for suitable coupling.

Roslan et al. [5] studied natural convection in a differentially heated square enclosure with a cylinder placed at the center of the enclosure. The shape of the cylinder was modified by increasing the number of sides but keeping the shape regular. This was done to understand the heat transfer and fluid flow characteristics of natural convection around different shapes. It was concluded that a square or circular geometry shows similar Nusselt number values at low thermal conductivities. Khozeymehnezhad and Mirbozorgi [6] did comparative research on how natural convection takes place in a square enclosure for a square or a circular cylinder placed inside of it. They came to understand that for lower Rayleigh numbers the transition from bi-cellular to unicellular takes place when a cylinder is close to the enclosure wall, but for higher-order Rayleigh number starting at 10^5 the vortex formed is always unicellular. It was also concluded that for all values of the Rayleigh number the average Nusselt number value of circular cylinder is always greater by some margin.

Ghaddar and Thiele [7] studied a 2D system of heat transfer for a heated horizontal cylinder continuously revolving about its central axis, placed in an isothermal rectangular enclosure. They showed that rotation of cylinder leads to an increase in Nusselt number values hence enhanced heat transfer through natural convection takes place.

Moukalled and Acharya [8] in their paper have compared how the aspect ratio of a cylinder placed concentrically inside a square enclosure affects the heat flow. The study also shows how an increase in aspect ratio causes a reduction in flow strength and thermal stratification as well as affecting the symmetry of upper and lower halves. Kim et al. [9] studied how natural convection takes place about a heated cylinder placed inside a cold square enclosure. 2-D solution for unsteady natural convection was obtained through Immersed Boundary Method (IBM). The maximum value for the average Nusselt number is obtained at distances closer to the bottom surface and for higher Rayleigh number values. Dasha and Lee [10] researched how natural convection inside a square enclosure is affected by diagonal as well as horizontal eccentric displacement of a square cylinder. The study also concludes that the heat transfer rate is dominated by conduction at lower Rayleigh number and is increasingly convective for higher Rayleigh number values. De and Dalal [11] have done a detailed study on natural convection around a tilted square cylinder (45°), by varying its aspect ratio and vertical position of a cylinder from the bottom wall. They also analyzed how the behavior of cylinder walls at constant heat flux or constant temperature behave and found a constant temperature system to be more efficient. It was also determined that aspect ratio affects systems heat transfer rate at lower Rayleigh number more than that at higher Rayleigh number.

Hussain and Hussein [12] have done an investigation on natural convection of uniformly heated circular cylinder placed inside a square enclosure. This paper also defines the fluid flow for change in cylinder's vertical position concerning the vertical central axis. The paper identified that the average Nusselt number increases with a decrease in distance between the walls of enclosure and cylinder also with the rise in Rayleigh number values. Minsung et al. [13] have done a study on the system of natural convection in a square enclosure with a circular cylinder placed at its center with varying Rayleigh number values. The study shows that with an increase in Rayleigh number, the distribution of streamlines and isotherm are affected, and this change is based on bottom wall temperature. Park et al. [14] in their paper describes a system of the square enclosure with differentially heated left and right walls. This system checks the effect of changing the position of cylinders to the enclosure. It was found that at lower Rayleigh number systems natural convection distribution is governed by cylinders position. But at higher-order Rayleigh number, the systems are governed by the cold walls of the enclosure. Yedder and Bilgen [15] in their paper have described a system of laminar natural convection for an inclined enclosure bounded by a solid body on one side. The system is given a constant heat flux emulating solar radiation input and the other 2 adjacent walls are adiabatic. Debayan et al. [16] in their paper have described a system of natural convection, with a square/circular cylinder placed at the center of a square enclosure. The main point of the study is how the sinusoidal distribution of heat over 2 adjacent enclosure walls and a heated cylinder affects systems buoyancy-driven heat transfer and volumetric entropy generation characteristics. Dutta et al. [17] have studied natural convection and heat transfer as well as entropy generation in rhombic medium inclined at 30° and filled with porous medium and air.

Man Yeong et al. [18] did a numerical study of natural convection and fluid flow for a system driven by temperature differences on its left and right wall. The study was conducted mainly on three fluids sodium, air, and water. The result shows that a sudden rise in temperature-difference causes the system to change from its initial Nusselt number values to some final values for a new steady-state system. Pishkar et al. [19] have studied unsteady natural convection flow for Newtonian and non-Newtonian in the square cavity for a wall oscillating at different temperatures for the surrounding. Torki and Etesami [20] in their paper have a behavior of SiO_2/water nanofluids at various inclinations in a rectangular enclosure for varying inclination. Tayebi and Chamkha [21] did numerical research to analyze entropy generation and natural convection under magnetic flow with Cu-Al_2O_3/water nanofluids in a square enclosure. Patrice et al. [22] present a paper on how to predict Nusselt number for a differentially heated square enclosure filled with Newtonian and non-Newtonian CNT nanofluids. Bahrami and Safikhani [23] in their study have introduced a porous medium to enhance heat transfer and have been applied on a rotating fixed inner cylinder kept inside an eccentric cylindrical wall to improve heat transfer. The results show that porous media with a higher Darcy Number enhances heat transfer. With the porous medium, there is a 90% increase in heat transfer in 0.1 Richardson number. Taheri et al. [24] the effect of how non-Newtonian fluid behaves in non-Fourier diffusion in an unsteady natural convection system.

Alina [25], two plates are placed sided by side to give an effect of a chimney. This causes the system to air rate and heat transfer coefficient, due to air velocity increase. An enhancement in 18% is seen for normal enclosure and one of 27% is seen in the oval enclosure. Ramesh and Venkateshan [26] have conducted an experimental study on laminar natural convection in a square enclosure with heated vertical walls and adiabatic horizontal walls and air as the medium of heat transfer. This study is carried out based on differential interferometer (DI), on the basis which it was concluded that radiative heat transfer is negligible due to the low emissivity of hot walls. This paper also shows the eminent correlation between Grashof number values and the Nusselt number. This research accurately shows how experimental value differs from computation value the amount deviation in results are there. It is also conclusively found that if the air is used as a medium for heat transfer, then for adiabatic conditions to be formed we require extra insulation on the walls of the enclosure. Cengel [27] many of the basic trends and formulae are studied and derived from this book based on chapter 6–9.

All these studies have shown that when an object is placed inside a square enclosure and if a temperature difference is there between the enclosure and cylinder walls, then the heat dissipation shall take place through means of natural convection. It was seen that in many of the literature how a change in orientation greatly affects heat transfer and fluid flow characteristics. A study by Ghaddar and Thiele [7] has further clarified how the continuous rotation of cylinders affects natural convection. But none of the paper seems to have considered how a change in a simple orientation such as rotation may directly affect the efficiency of heat dissipation through means of natural convection, also a thorough study on flow characteristics such as velocity magnitude, vorticity magnitude, etc. is not present for the assumed kind of system. Hence, the present study tries to fulfil these requirements by analyzing the effect of the rotation of cylinder on heat transfer through natural convection and flow characteristics of the system. We also tried to find the most optimum configuration of the cylinder for maximum heat dissipation rates. Analysis of free convection at low Rayleigh number is also done.

Problem statement

A two-dimensional square cylinder which is kept inside a square enclosure is studied. The length of the enclosure is H and the diagonal length of the square cylinder is L which is 4/10H (Fig. 1). The enclosure walls are kept at isothermal constant temperature T_c (300 K at all times, taken according to a calculation done by Khozeymehnezhad and Mirbozorgi [6]) and the cylinder walls at higher temperature T_h which is constant and isothermal for each case. The walls of the enclosure as well as the cylinder are made of standard aluminium. The fluid property is defined by its averaged temperature taken as a constant and density/ which is determined through means of Boussinesq approximation. The study is conducted by varying Rayleigh Numbers ranging from 10^4, 10^5, and 10^6. In this case, the Rayleigh number is used to define the non-dimensional value of viscous force which is dependent upon the change in temperature around the square cylinder. The system is studied by analyzing flow characteristics about a cylinder whose orientation is changed by rotating it by $\theta = 15°$(for angles 0°, 15°, 30°, 45°, 60°and 75°) and Prandtl number which is taken as 0.7. All this computation is done by the use of ANSYS FLUENT 2018 software and the plots and diagrams are made in TECPLOT. This study is parametric and the input data are adjusted to give dimensionless values.

Formulae

The system was analyzed based on multiple numbers of non-dimensional values:

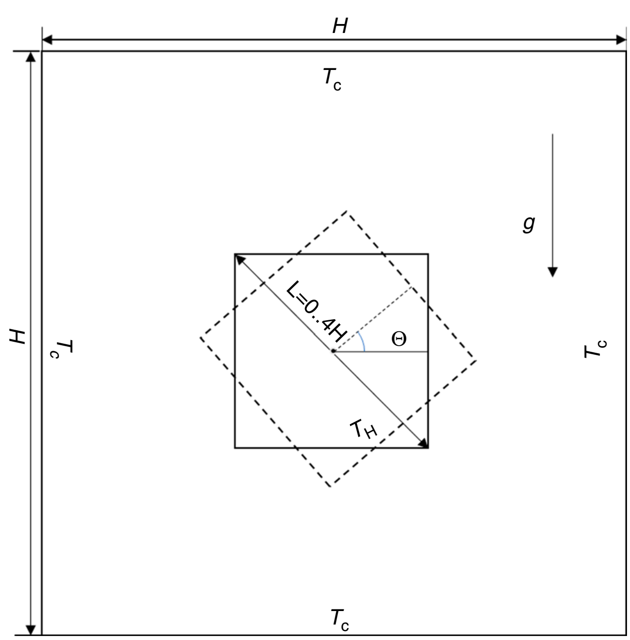


Fig. 1 Schematic representation of the different orientations of the Square cylinder inside a square enclosure

Rayleigh number

Rayleigh number is used to define the sidewall temperature of a square cylinder to the enclosure. Rayleigh number is used to define whether the flow of a fluid system is laminar or turbulent during the natural convection boundary layer. The values of the Rayleigh number vary from 10^4 to 10^6. This is the ratio of buoyant force vs thermal and momentum diffusivity.

$$Ra = \frac{g.\beta.\left(T - T_{\infty}\right).L^3}{v.\alpha} \tag{1}$$

$$T_h = \frac{Ra. \propto .\vartheta}{g.\beta.H^3} + T_c \tag{2}$$

Nusselt number

A Nusselt number is a non-dimensional number used to define the ratio of convective heat flow to conductive heat flow. The value of the Nusselt number in our case is used to define how effectively natural convection is taking place at different thermal boundary layers.

$$Nu = h\frac{L}{k} \tag{3}$$

Skin friction coefficient

Further, the analysis of the system is also done based on skin friction coefficient C_f, which is a non-dimensional number representing the ratio of shear stress over a body to dynamic pressure applied due to the flow. The positive rise in Skin friction value leads to an increase in convective heat transfer. In our study, both local and average Skin Friction values are determined for each case. Skin Friction is found by:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho v^2} \tag{4}$$

Pressure coefficient

The system is also analyzed for the pressure coefficient which is the non-dimensional ratio of the difference in pressure difference on the surface against that of free stream pressure, the inertial force, or the kinetic energy of free stream. This can help us know whether the force acting on a surface is negative or positive pressure with a change in velocity flow over a surface. A positive pressure coefficient means that there is an increase in pressure on the surface of the body or localized region and airflow is slow, and with a negative pressure coefficient, we observe a decrease in pressure on the surface or localized region and an increase in fluid velocity. The increase in pressure increases drag on the surface and the decrease in pressure reduces drag on the surface. This is given by:

$$C_{\mathrm{p}} = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2} = \frac{p - p_\infty}{p_\circ - p_\infty} = 1 - \left(\frac{V}{V_\infty}\right)^2 \tag{5}$$

Governing equations, boundary conditions, and solution procedure

The general governing equations for fluid flow and heat transfer have been reduced to 2-D form by incorporating suitable assumptions and presented in means 6–9.

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{6}$$

x-Momentum equation

$$\rho\left(u\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{7}$$

y-Momentum equation

$$\rho\left(u\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta\left(T - T_\infty\right) \tag{8}$$

Energy equation

$$u\left(\frac{\partial T}{\partial x}\right) + v\left(\frac{\partial T}{\partial y}\right) = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{9}$$

The equations are discretized and solved using the finite volume method (FVM) for suitable boundary conditions. No-slip boundary condition is taken as a parameter for the walls of enclosure and cylinder. The system is driven by the difference in temperature between the cold walls of the enclosure and the hot walls of the cylinder as described in the problem statement. Second-order upwind scheme and central difference scheme are used to discretize the convective terms and diffusion terms in the governing equation.

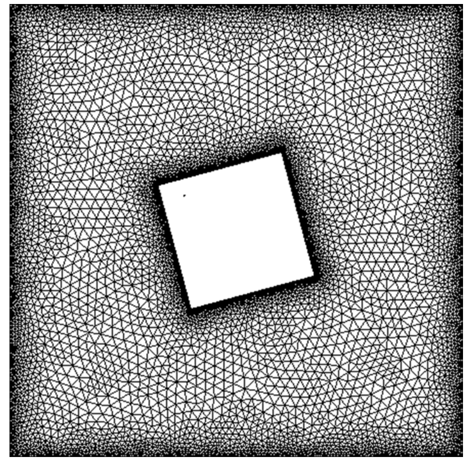


Fig. 2 Computational domain with meshing

As the central difference scheme has a better convergence rate than other finite difference methods, such as forward and backward difference when it comes to advection–diffusion terms related to discretization. A SIMPLE algorithm

Table 1 Grid independence study

No. of elements	Nusselt number	Percentage of variation
14,696	14.139	–
17,434	14.135	0.028
19,022	14.131	0.028

is used, and the residuals were in the order of 10^{-6} for the mass, momentum, and 10^{-12} to achieve convergence.

Grid generation and grid independence

The study for grid generation and independence has been done, and it has been found that the use of a structured grid was insufficient and gave unsatisfactory results. Hence, an unstructured triangular mesh (Fig. 2) was used for simulations and parametric result finding. The grids side walls are divided into 100 soft nodes and then discretized. It was seen that the result obtained were satisfactory by nature for the number of elements 14,696 and is in the acceptable range as seen in Table 1. This kind of grid was inspired by studies done by Roslan et al. [5].

Table 2 Average Nusselt number validation on isothermal body

Ra	Kim et al. [9]	Kim et al. [13]	Present study	% Difference in column 2 and 4	% Difference in column 3 and 4
10^4	5.108	5.11	5.13	0.429	0.39
10^5	7.767	7.75	7.82	0.68	0.89
10^6	14.11	14.2	14.21	0.7	0.07

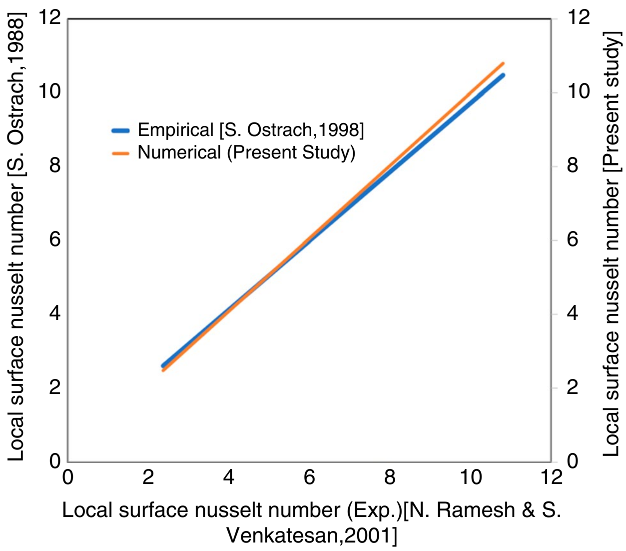


Fig. 3 Comparing local surface Nusselt number of the present study with theoretical value by Ostrach [1] and experimental value by Ramesh and Venkateshan [26]

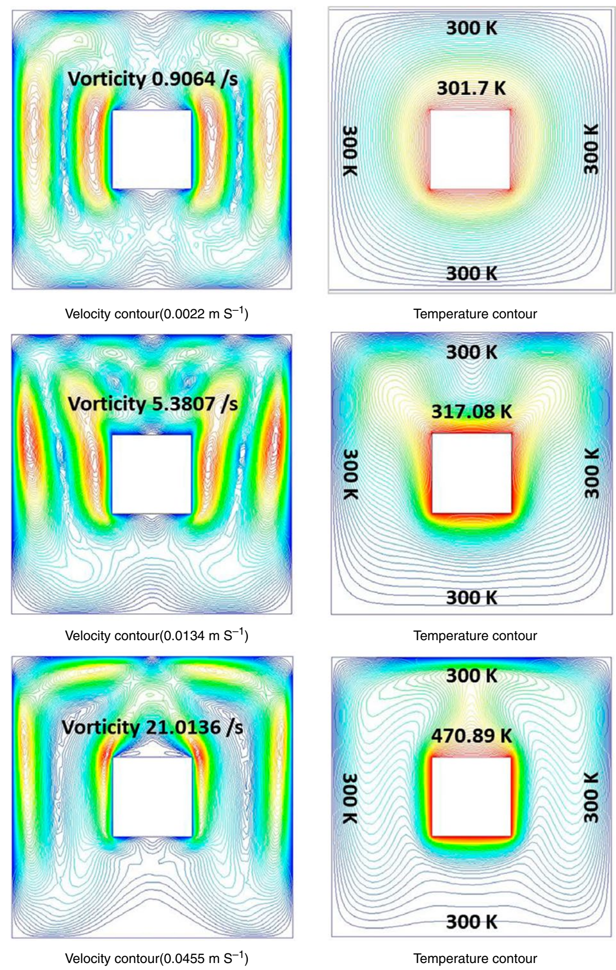


Fig. 4 Velocity and temperature contour for 0° change for different Rayleigh numbers (10^4–10^6)

Results and discussion

Validation

This study was validated on basis of a study done by Kim et al. [9] and Kim et al. [13] which numerically analyzed the problem by taking the input value of $H = 0.04$ m and length of the square cylinder being $0.04H$. The cold wall temperature of the enclosure was taken as 300 K and the Rayleigh number varies from 10^4 to 10^6. The average Nusselt number of the present study is compared and found the variation of less than 1%.

Experimental studies were conducted by Ramesh and Venkateshan [26] for natural convection system with air as a medium, for the system. The top and bottom walls were made adiabatic, to fulfil the boundary condition. The values acquired by them were compared against those values which are obtained by Ostrach [1]. They are verified to be true with only minor changes present between experimental and computational data as can be seen in Fig. 3. The values acquired by the present study were compared against the experimental value and the line was plotted as seen in Fig. 3 as a Numerical line. We can observe that only a minor deviation from the original study to the present study and a general linear trend is observed in both cases. Hence, the present study is validated experimentally through comparison of data.

Velocity and temperature contours

The present study is based on an analysis of velocity and temperature contours along with various types of the plot of,

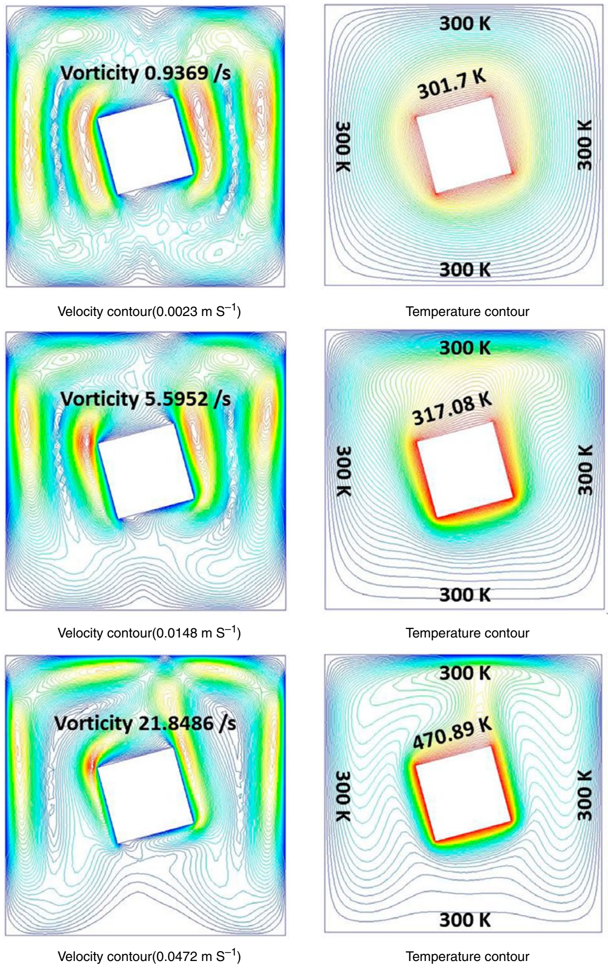


Fig. 5 Velocity and temperature contour for 15° change for Rayleigh numbers 10^4, 10^5 and 10^6

skin friction number (average and local) and local pressure coefficient and Nusselt number (average and local).

Performance of heated square obstacle

The study of Fig. 4 shows velocity and temperature contours for increasing value of Rayleigh number at 0° rotation of the square cylinder. With an increase in the Rayleigh number, we observe an increase in the velocity magnitude of the system, as well as an increase in average vorticity magnitude. This phenomenon is seen due to differential heating of the system leading to a complex flow formation. The differential heating leads to a rise in temperature of the fluid in a certain localized region through means of heat conduction from the wall to the fluid, which leads to a change in density of the fluid (either an increase or a decrease). The difference in density causes buoyant forces to act in the system leading to the formation of flow circulation. The range wherein this change takes place can be understood by studying the temperature contours in Fig. 4. The hotter fluid moves up and outward while colder fluid moves down and toward the center, replacing the fluid surrounding the cylinder. The hot fluid which moves outward is cooled by transferring its heat to enclosure walls. This cycle of heating and cooling repeats to create a flow circulation around the enclosure. This flow circulation as well as the difference in kinematic viscosity of fluid leads to a rise in cross circulation and vortex formation around the cylinder. Hence, a system of two vortex systems is formed on the left and right side of the cylinder.

From the above description, we can comprehend that differential heating leads to heat and mass transfer, and this temperature difference is governed by the Rayleigh number. Hence, we understand why a rise in Rayleigh number leads to an increase in velocity and vorticity magnitude and formation of recirculation region above the cylinder. This type of fluid flow system is defined as natural convection, which is dependent on both conduction as well as advection for heat and mass transfer.

As natural convection is affected by pressure inside the system hence pressure coefficient is studied for each case. In Fig. 10, the local pressure coefficient data for a system of different Rayleigh numbers are given. Further analysis reveals that the maximum value is closer toward the inclination of around 180°. This means that the region is closer to the edge centre dominated by pressure applied and hence conductive heat transfer takes place at the surface. Toward the corner, as pressure reduces advective heat transfer dominates the system hence a high-velocity region is formed around the edge of the cylinder. The same can be seen in Fig. 11 with skin friction being dominant around the sides and less around the edges, which leads us to understand that conductive heat transfer takes place at the sides of the cylinder. Observing the velocity contour in Fig. 4 and local pressure coefficient value in Fig. 10 we see that at lower values of Rayleigh number the system has bifurcation of flow at top and bottom causing 2 separate vortex system to be formed on the sides of the cylinder, but from $Ra = 10^5 - 10^6$ we observe no bifurcation of flow at the top, the flow just combines on top of the cylinder. We observe that in Fig. 13 with an increase in Rayleigh number an increase in skin friction coefficient is seen. The system also shows a similar trend as its local skin friction coefficient for the local Nusselt number as it dominant around the sides rather than the edges of the cylinder

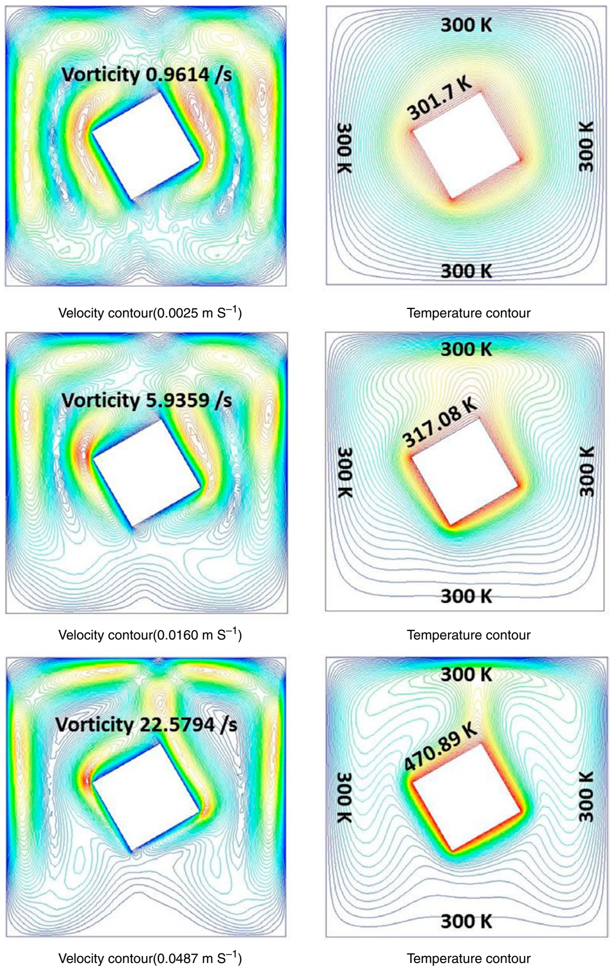


Fig. 6 Velocity and temperature contour for 30° change for Rayleigh numbers 10^4, 10^5, and 10^6

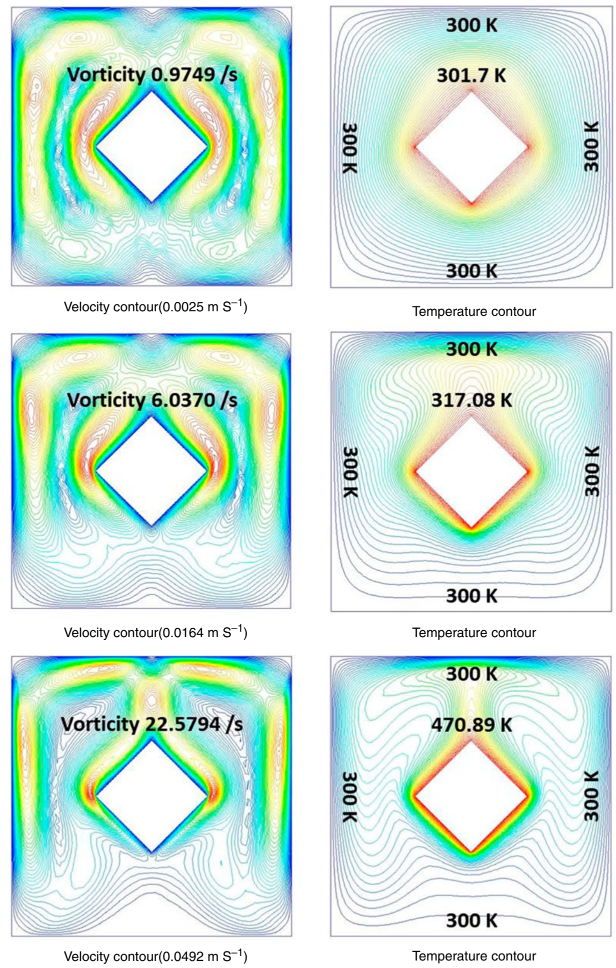


Fig. 7 Velocity and temperature contour for 45° change for Rayleigh numbers 10^4, 10^5 and 10^6

(as seen in Figs. 11 and 12). All these phenomena allow us to understand that with an increase in temperature difference and Rayleigh number convective heat transfer increases around the sides of the cylinder, which leads to a rise in average Nusselt number as observed in Fig. 14. Hence we perceive that the system follows rules previously pertained to natural convection.

Performance of 15° and 30° rotated the heated square cylinder

In this case, the square cylinder is tilted to 15° anticlockwise direction to its center, as seen in Fig. 5, we observe the formation of twin vortex on the sides of the cylinder as seen in the first case. But the rest of the fluid properties show much variation, such as a relative rise in average velocity magnitude and average vorticity magnitude of the system. This change can mostly be explained on basis of the edge of the square cylinder piercing into the vortex system which leads to a shift in heat transfer rate; this is because the effective heat transfer at corners wherein heat is concentrated takes place. This is caused as fluid separation does not take place at the corners. This shift leads to an earlier interaction of fluid current at a lower Rayleigh number by not allowing bifurcation of fluid to take place and hence flow re-circulation happens as seen in temperature contours in Fig. 5. This causes more convective heat transfer taking place near the corners, hence leading to an increase in average Nusselt number as compared to 0° change rotation. This scenario also leads to the shifting of flow circulation to be skewed toward the right corner of the cylinder. This, in turn, leads to the relative increase of velocity magnitude, vorticity magnitude and this trend keeps on magnifying with the gradual

Fig. 8 Velocity and temperature contour for 60° change for Rayleigh numbers 10^4, 10^5 and 10^6

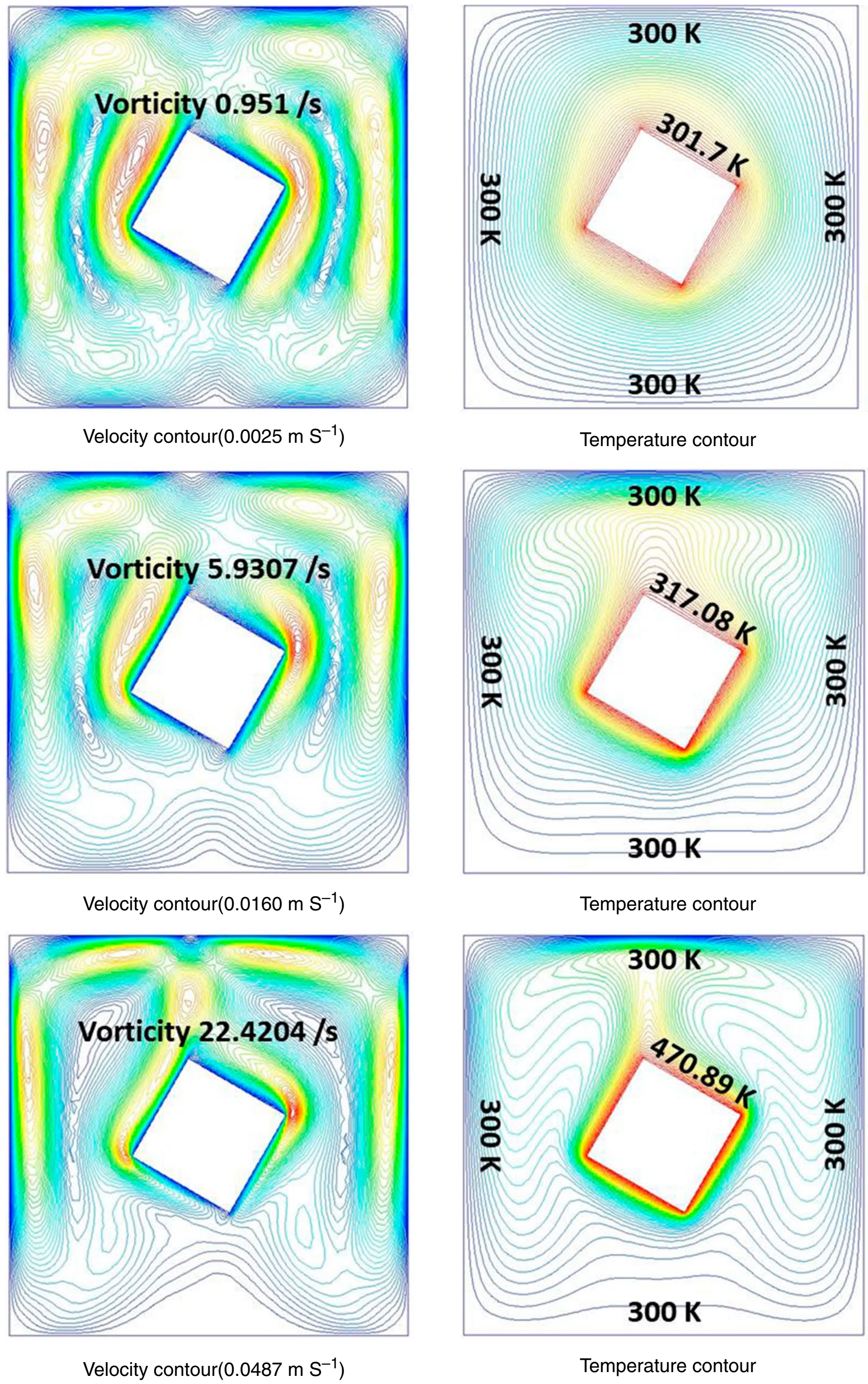
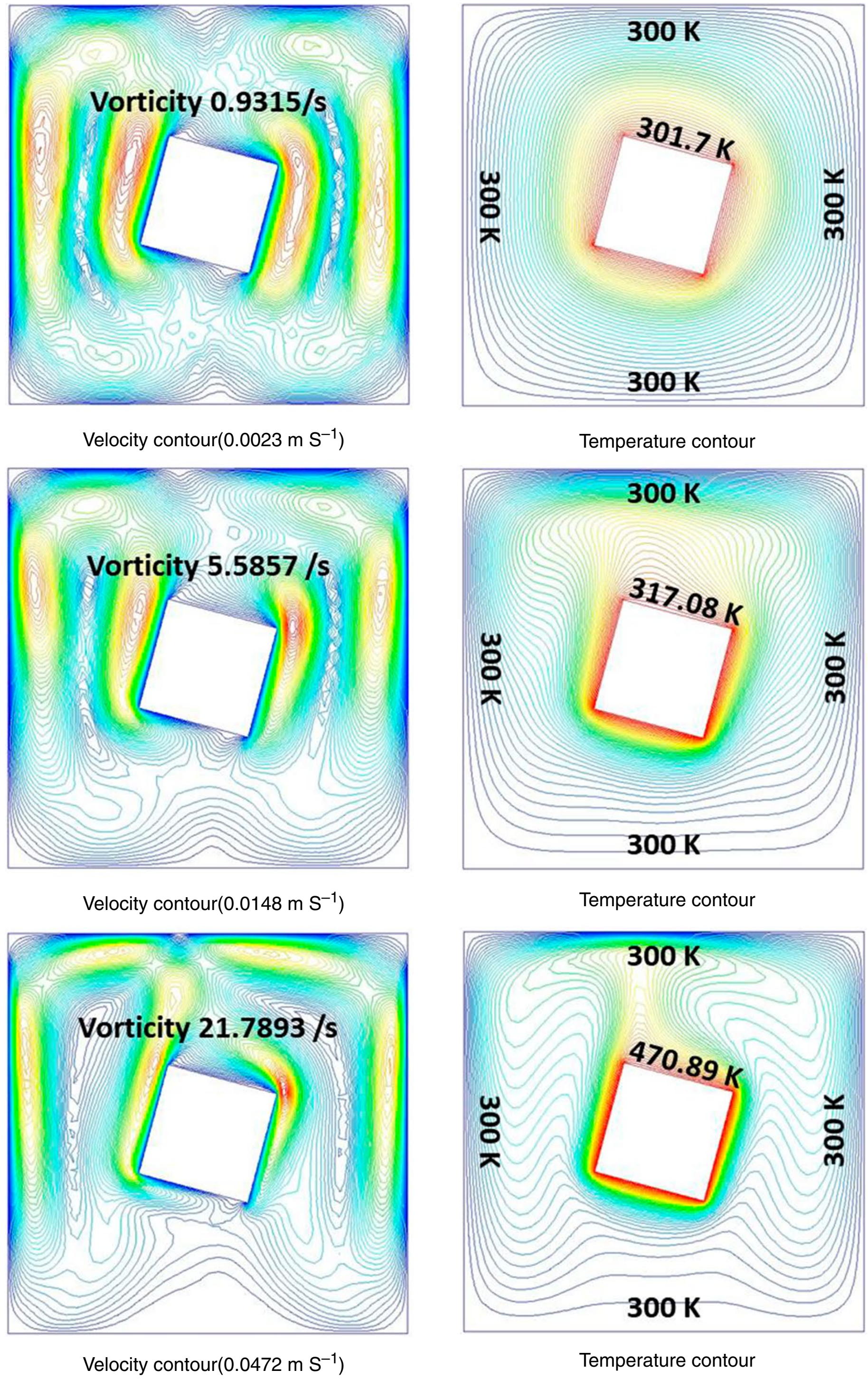


Fig. 9 Velocity and temperature contour for 75° change for Rayleigh numbers 10^4, 10^5 and 10^6



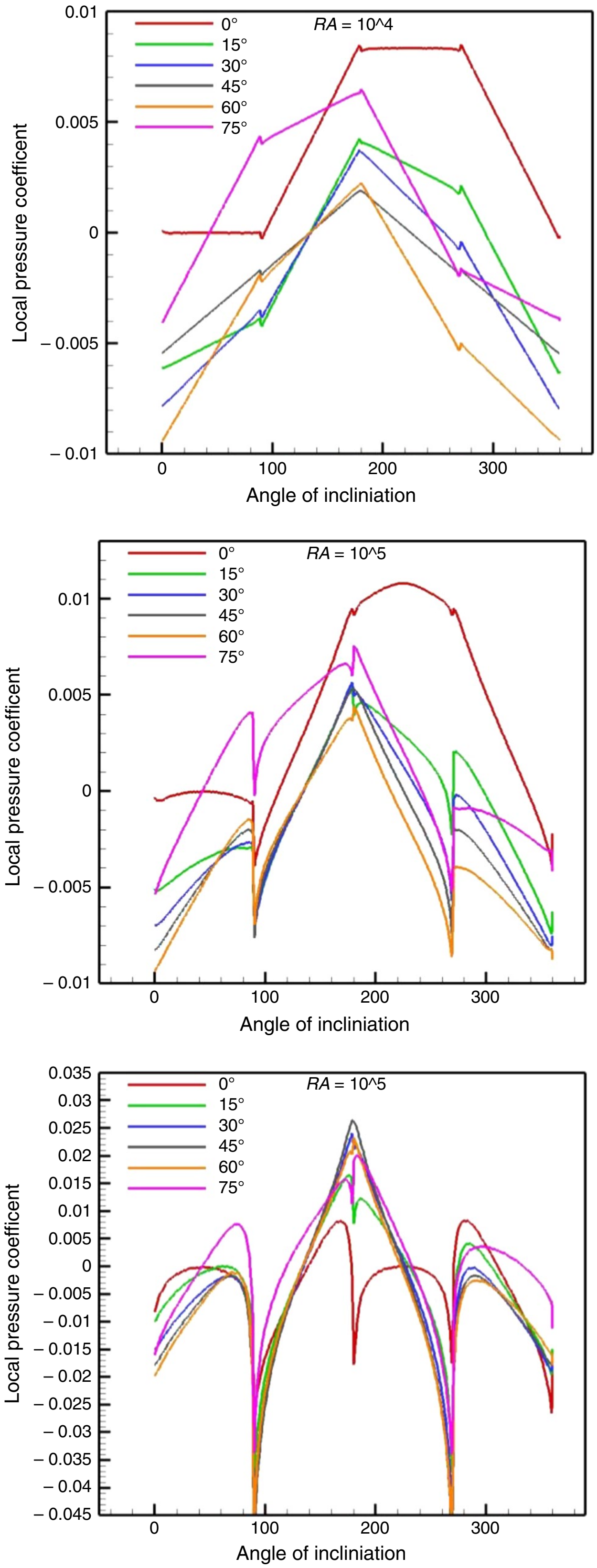


Fig. 10 Local Pressure coefficient versus angle of inclination for different *Ra* numbers

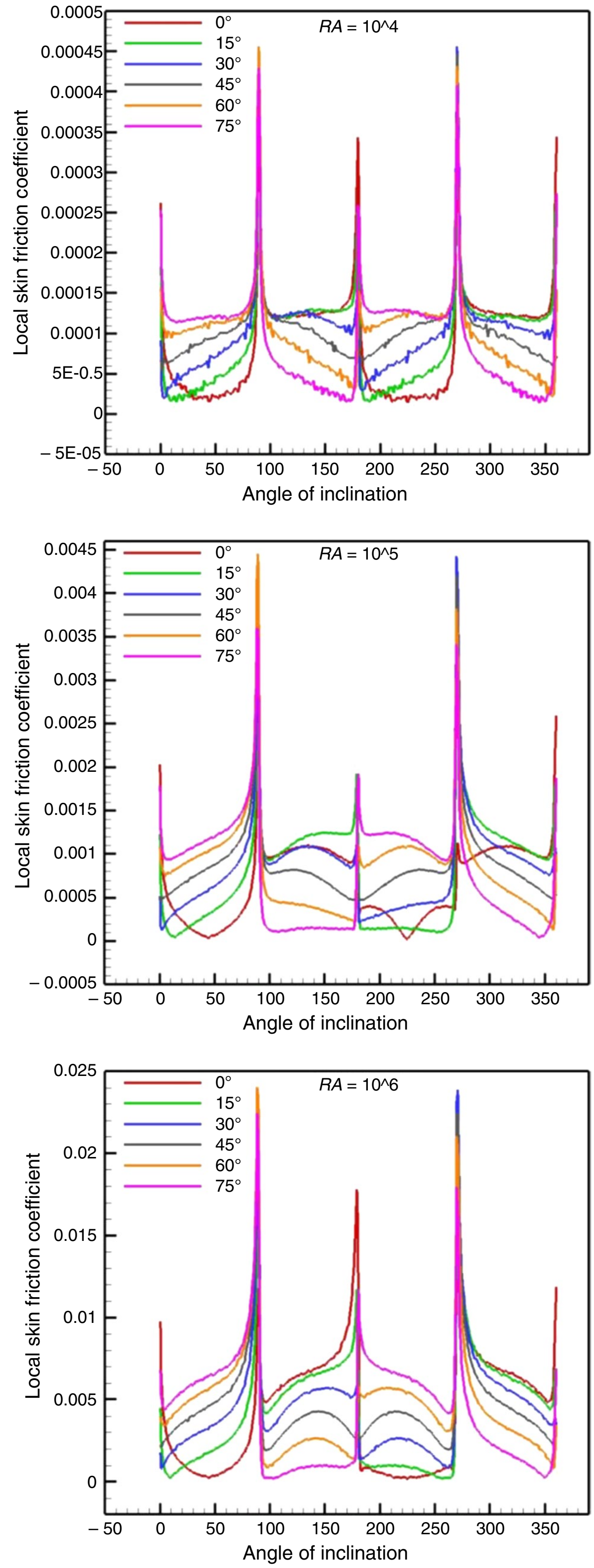
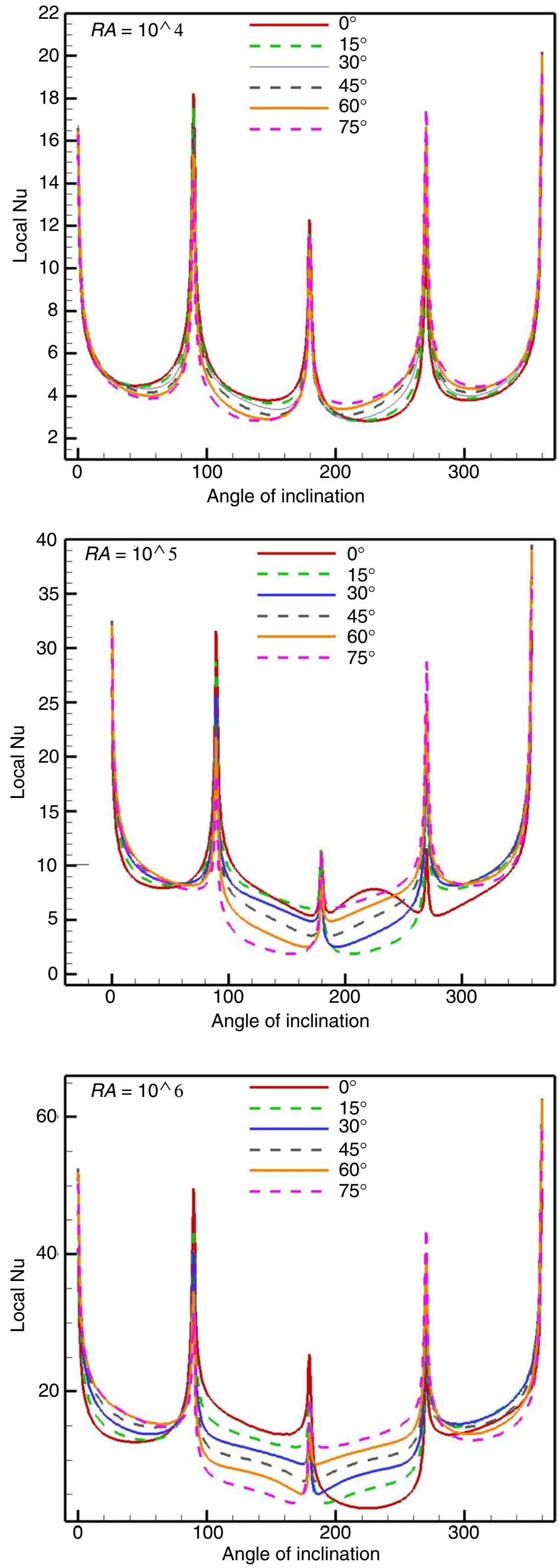


Fig. 11 Local Skin friction coefficient versus angle of inclination for different *Ra* numbers

Fig. 12 Local Nusselt number versus angle of inclination plot for different Ra numbers



rotation of square cylinder by 15° each up to a certain limit. This idea is further corroborated by studying Fig. 6 for 30° rotation of the cylinder and by observing velocity and vorticity magnitude for Figs. 4–6. From the observation of the three figures we understand a trend that with an increase in Rayleigh number, velocity and vorticity magnitude also increases. Observing the graph in Fig. 12 tells us about the increase in local Nusselt number value around the edge of the cylinder; this is caused by an increase in heat transfer rate toward the edge of the cylinder due to its slight rotation. This overall dynamic change brings about an increase in average Nusselt number compared to the previous case (as seen in Fig. 14). We also observe that the skin friction coefficient for both 15° and 30° rotation increases with the rise in Rayleigh number values. Another factor to be noticed is that between each rotation value of the skin friction coefficient increases for a similar Rayleigh number (as seen in Fig. 13). This shows that friction drag affecting the body increases with the rotation of the cylinder. The value of the local skin friction coefficient also follows the trend followed by the local Nusselt number as seen in Figs. 11 and 12. This shows us that with the rotation of the cylinder, friction drag affecting the body shifts toward the corner of a cylinder. This causes flow separation to take place toward the top edge of a cylinder with each successive rotation for a lower Rayleigh number. Figure 10 shows how local pressure coefficient values for both systems average out to be negative hence the pressure drag acting on the body is mainly less. Figure 10 plot for Rayleigh number 10^4 further prove the point that flow separation takes place at the top edge but decreases with increase in rotation as well as Rayleigh number, this can be seen by drawing a parallel line about x-axis passing through the very first point on the left of the plot for 15° and 30° rotation the line touches the plot again at a point just before the 90° mark for inclination hence showing that flow separation happens at that point.

Performance of 45° rotated the heated square cylinder

The maximum value of velocity magnitude and vorticity is achieved when a square is tilted 45° to horizontal. This can be understood by comparing values of vorticity and velocity magnitude in Figs. 4–9. This may be happening due to the even and symmetrical penetration of the top corner of a cylinder into the vortices which leads to an increase in heat dissipation. This leads to the formation of a much more concentrated recirculation point just above the top edge of the square. Another important point to be noted is that the maximum value of the Nusselt number is achieved

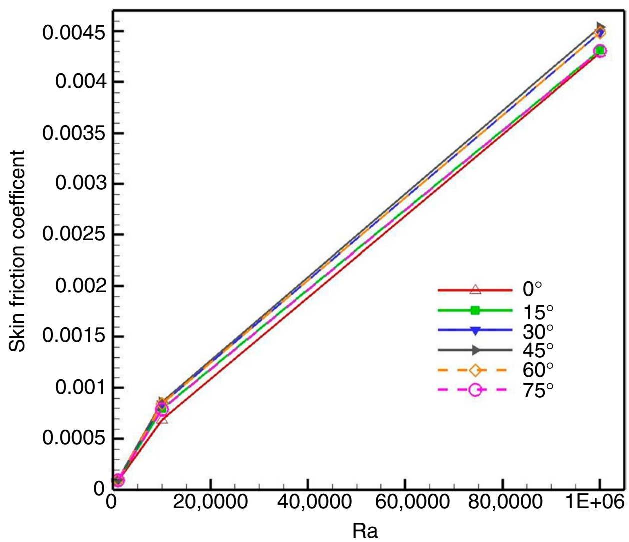


Fig. 13 Average Skin friction versus different Rayleigh numbers plot

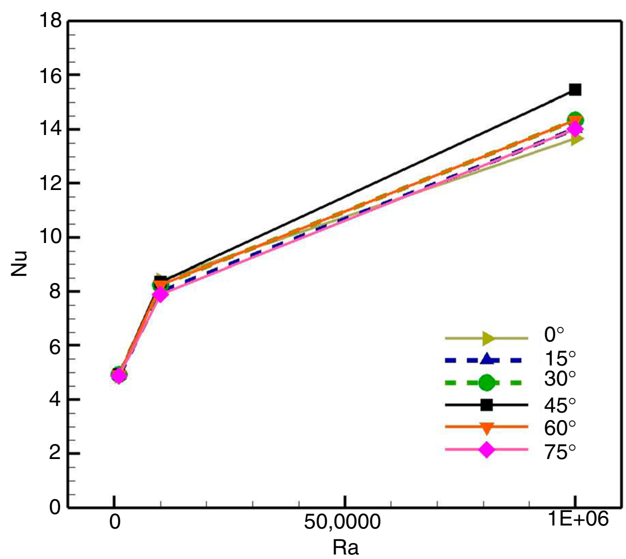


Fig. 14 Average Nu vs different Rayleigh numbers plot

at 45° rotation for Rayleigh number value 10^6 compared to the rest of the values as seen in Fig. 14. Figure 12 shows the value of Local Nusselt number for a different angle of inclination around the cylinder and it shows how the maximum local Nusselt number are obtained at the corner of the cylinder in this case, hence maximum convective heat transfer is taking place at the corners of this system especially at the top and bottom corner. According to Fig. 13 the maximum value of skin friction coefficient is also obtained for 45° rotation of square obstacle as compared to other systems. This result shows that the value of drag force is highest for 45° rotation. Figure 11 describes how local skin friction coefficient is maximum at corners of cylinder specifically at the top and bottom corner of the cylinder. This can be inferred as friction drag being highest at the top and bottom corner of the cylinder, and to be the smallest on the sides of the cylinder. Figure 10 shows how the value for pressure coefficient is negative throughout the major portion of the system and hence proves that friction drag dominates pressure drag on the surface. We also observe that the skin friction coefficient never reaches the same point as the first value for 45° rotation for all three Rayleigh numbers throughout the whole surface, which means that flow separation never occurs throughout the surface of the body. Hence, allowing for an effective convective heat transfer to take place.

Performance of 60° and 75° rotated heated square obstacle

After careful observation of contours and plots of 15° and 75° rotation (Figs. 5 and 9), the values of vorticity and velocity are similar for the different cases of Rayleigh number, and if we observe their corresponding Nusselt number value and Skin friction coefficient value in Figs. 14 and 13 we observe that they are the same. This shows that they have very similar convective heat transfer systems as well as drag force affecting their body.

By observing their local Nusselt number value, local Skin friction coefficient value in Figs. 11 and 12 for different values we observe another fact that the plot for both 15° and 75° rotation is a mirror image of each other and follow the same trend but in the opposite order. The same can be said for its Pressure coefficient data (as seen Fig. 10) as the values are a mirror image of each other but at different heights may be due to the minor variation in flow, from this we can also conclude that their flow separation takes place at points but at opposite sides. Hence it can be concluded that the values obtained for 15° and 75° rotation are not just physically flipped over imagïrror image of each other about a vertical axis passing through the mid-points of the enclosure. This same trend can be seen for 30° and 60° rotation (Figs. 6, 8, 10, 11–13). Hence it conclusively shows how the values of mirror-imaged objects show similar flow characteristics. No further rotation of square cylinder is required, as all orientation of square for 15° series are analyzed and studied in the given paper, and the rest is just repetition of given figures or mirror images of the same (Fig. 14).

Conclusions

In this study, the flow and heat transfer analysis for different orientations by rotating the square cylinder about its central axis is done. The variable temperature of the enclosure and cylinder was analyzed and reported with necessary contour plots and figures. With this study, we have computationally proven that an increase in Ra number leads to an increase in Nusselt number. We also saw that the effects of how a change in the shape of a regular polygon affects the behavior of fluid and heat dissipation rate.

1. It's concluded that Nusselt number for various regular polygon which is symmetric for the enclosure show similar values for rotation of 15° and 75° and 30° and 60°. With rotation which is a mirror image of each other showing similarly mirror-imaged temperature and pressure contours. Hence the main objective of how the rotation of squares can affect heat transfer rate was studied thoroughly.
2. We also see that with each successive rotation that leads to the orientation of 45°, 135°, 225°…. With the angle of the plane of one side with horizontal of the enclosure, the system has an increase in velocity as well as vorticity magnitude. This is caused by flow separation taking place at some point on the edge rather than the corners of it as the point with the most effective heat transfer through a conductive medium.
3. Comparing a square at the different rotation of 0°, 15°, 30°, 45°, 60°, and 75°, we infer that 45° angle of rotation gives the most optimum and efficient means for heat transfer in a natural convection system for higher Rayleigh number with the peak being 10% more than the least value. This is due to the formation of an efficient recirculation system of vortices, which allows efficient and fast transfer of heat around a major portion of the cylinder
4. It was also observed that skin friction drag helps heat transfer through a convective medium as the drag influences turbulent flow and vortices to be formed. Whereas an increase in pressure drag causes the system to behave more like a conductor in nature, which is less efficient compared to convective heat transfer as stated in the 5th chapter of [27].

Hence an electronic system oriented at 45° for ground will show the most efficient mode of cooling through means of natural convection, allowing an overall reduction in budget and computational loss in any electronic system. This paper will allow the effective production of electronic cooling devices.

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