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# Forced Convection of Cu-Water Nanofluid in Vented Square Enclosure with an Interior Rotating Hexagonal Cylinder

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## ABSTRACT

This research presents the results of a numerical study of forced convection in adiabatic square ventilated enclosure containing a hot hexagonal cylinder rotating around its axis. The direction of the forced flow of Water-copper cooling nanofluid is perpendicular to the axis of the cylinder. The governing equations of the flow for an incompressible Newtonian nanofluid are assumed to be two-dimensional, steady and laminar. The finite volume method is used for numerical simulations. A series of calculations are carried out to study the effects of the main influencing factors; Reynolds numbers ($200 \leq Re \leq 1000$), rotational Reynolds numbers($-30 \leq Re_{\omega} \leq 30$), nanoparticle volume fractions ($0 \leq \varnothing \leq 3\%$) and hexagonal cylinder rotation direction on the heat transfer enhancement. The results show that the increase in the entry speed of the nanofluid into the cavity as well as the increase in the hexagonal cylinder's angular velocity increases the heat transfer between the hot hexagonal cylinder's and the cold nanofluid. The increase in the nanoparticles volume fraction only increases the heat exchange rate in the cavity when the inlet velocity reaches the value corresponding to a Re number equal to 1000.

## 1. INTRODUCTION

The phenomenon of heat transfer in fluid inside a vented enclosure is one of the most common problems in thermal engineering. In recent years, researchers have come up with the idea of replacing conventional fluids with nanofluids because of their ability to increase the rate of heat transfer. Among the topics that have been the subject of certain scientific investigations is the classical problem of heat transfer and nanofluid flow in a rectangular or square cavity containing a stationary block. Some researchers considered the block inside the cavity to be rotating, but few considered it hexagonal in shape, despite its widespread presence in many industrial applications such as solar power, cooling of electronic equipment, rotating tube heat exchangers, nuclear reactors, etc.

Jasim et al. [1] conducted a numerical investigation of the impact of an internal rotating cylinder within a ventilated cavity on the mixed convection of a hybrid nanofluid. Using the finite volume technique, the team solved the two-dimensional governing equations of mixed convection flow for the hybrid nanofluid (($Al_2O_3$-Cu)/(Water)). They evaluated the impact of several parameters, such as nanoparticle concentrations, cylinder radius, cylinder location, angular rotational velocity, Grashof numbers, and Reynolds numbers. The findings showed that the energy transport of the hybrid nanofluid improved with an increase in the concentration of solid particles, but it was accompanied by a rise in pressure drop. The study revealed that rotating the cylinder counter-clockwise leads to an improvement in convective heat transfer, whereas clockwise rotation has the opposite effect. Mehrizi et al. [2] analysed the impact of suspending copper nanoparticles on mixed convection in a square-shaped cavity by using the lattice Boltzmann method. The cavity features inlet and outlet ports and a centrally located hot obstacle. The study examines the effect of varying the location of the outlet port on heat transfer rate, and then looks at how the volume fraction of nanoparticles affects heat transfer at different outlet port positions. The obstacle walls are assumed to have an isothermal boundary condition, while the cavity walls are adiabatic. Results indicate that by incorporating nanoparticles into the base fluid and increasing their volume concentration, the heat transfer rate is improved for different Richardson numbers and outlet port positions. In the research carried out by Selimefendigil and Öztop [3], the impact of an inner stationary cylinder equipped with an elastic rod-like extension on the mixed convection of CNT-water nanofluid in a 3D vented cavity was numerically analyzed using the finite element method. The effects of various parameters, including Reynolds number, size of the circular cylinder, and CNT-nanoparticle solid volume fraction, were examined to determine their impact on the convective flow in the vented cavity. The results indicated that the addition of CNT nanoparticles significantly enhanced the average heat transfer rate by approximately 60% at the highest solid volume fraction of nanoparticles and this enhancement was not dependent on the obstacle geometric parameters. Boulahia et al. [4] conducted a numerical study to examine mixed convection flow in a square cavity with a circular cooling obstacle that is vented. The Navier-Stokes, continuity, and energy balance equations were solved using the finite volume method. The impact of the Richardson number, outlet port location, and volume fraction of nanoparticles was analyzed. The outlet port was positioned from the top to the bottom in order to identify the maximum heat transfer rate. The results showed that the heat transfer rate was enhanced by increasing the volume fraction of nanoparticles and decreasing the Richardson number. Additionally, it was discovered that the best configuration for improved heat transfer was achieved when the outlet port was located at the bottom of the vented cavity. Dutta et al. [5] explored the impact of mixed convection and heat transfer on a $Al_2O_3$-Cu/viscoplastic hybrid nanofluid in a ventilated enclosure. The study involved injecting a cold viscoplastic hybrid nanofluid through the inlet located in the lower left corner of the enclosure, while the outlet was situated at the lower right corner. A heated solid obstacle was placed at the bottom wall of the enclosure and the left wall was considered uniformly heated. The results showed that the addition of Cu-nanoparticles to the $Al_2O_3$⁄viscoplastic fluid improved heat transfer, but the yield stress of the fluid reduced heat transfer while increasing entropy generation. An increase in the conductivity ratio of the solid to fluid intensified both heat transfer and entropy generation, with heat transfer outpacing entropy generation. Moayedi [6] studied the heat transfer enhancement of copper-water nanofluid in a vented square enclosure with four configurations of two cylinders in rotation. The results of this numerical investigation showed that the higher the nanofluid volume ratio and the higher the rotational Reynolds number, the higher the mean value of the Nusselt number. The study also determined which configuration among the four leads to the best heat transfer rate. Moreover, the results indicated that there is an optimal Reynolds number (Re=600) for which the average Nusselt number is maximized. Three different nanofluids (Cu, $Al_2O_3$, $TiO_2$) have been considered in the numerical study by the finite volume method made by Boulahia et al. [7], on the three modes of convection (natural, mixed and forced) inside a ventilated cavity containing inside a cold obstacle of two different configurations (square and triangle). The authors concluded that for different Richardson numbers, the increase in the percentage of nanoparticles leads to a significant increase in the Nusselt number, i.e., an improvement in the heat transfer rate. They found that the Cu-$H_2O$ nanofluid is the most efficient in heat transfer compared to the other two considered nanofluids. Abderrahmane et al. [8] conducted a numerical study to evaluate the effect of a rotating inner cylinder on mixed convection of $Al_2O_3$-Cu⁄CMC hybrid nanofluid in a vented cavity. The 2D steady laminar flow of the incompressible power-law non-Newtonian nanofluid was solved using the finite element method. The results indicated that a counter-clockwise rotation of the cylinder leads to improved heat transfer, while clockwise rotation has the opposite effect. Additionally, the heat transfer improved as the cylinder approached the hot wall when rotating counter-clockwise. Selimefendigi and Öztop [9] investigated the influence of a rotating bundle of tubes on the hydrothermal performance under forced convection in a ventilated cavity using numerical simulation. The mixture of Ag and MgO nanoparticles suspended in water and CNT-water nanofluid served as the hybrid nanofluid. The numerical analysis was carried out using the finite volume method, and the results showed that the rotational effects of the tube bundle have a positive impact on the hydrothermal performance. As the solid concentration of nanoparticles increased, the average Nu values of the CNT-water nanofluid and the Ag-MgO/water hybrid nanofluid began to diverge. Selimefendigil and Chamkha [10] investigate the mixed convection of CuO-water nanofluid in a three-dimensional cavity equipped with inlet and outlet ports, and the effects of an inner rotating circular cylinder, a homogeneous magnetic field, and corrugated surface on the heat transfer. Results showed that the addition of nanofluid increased the Nusselt number by 5% when compared to the motionless cylinder case, due to the enhancement of thermal and electrical conductivity. The study also found that the average heat transfer rate increased by 9.5% for counter-clockwise rotation at an angular rotational speed of 30 rad/s on the corrugated surface. Studies [11-18] have primarily concentrated on the flow of fluid in cavities with obstacles, lacking the presence of nanoparticles.

This study numerically simulates the steady flow and heat transfer mechanisms in a two-dimensional adiabatic square cavity vented with Cu-$H_2O$ nanofluid and containing a rotating hexagonal cylinder (clockwise and anti-clockwise) that is maintained at a high temperature compared to that of the nanofluid at the inlet of the cavity. This configuration is broadly found in industrial applications, especially in the cooling systems of electronic components and the design of solar collectors. To the knowledge of the authors, this configuration has not been addressed by previous scientific studies. The values of the nanofluid inlet velocity are chosen so that the flow regime remains laminar ($200 \leq Re \leq 1000$), likewise for the angular velocity of the cylinder ($-30 \leq Re_\omega \leq +30$). The stationary cylinder's limit situation without rotation is also considered. The main goal of this study is to develop a numerical scheme based on the finite volume technique to find the optimal rate of heat transfer by combining the influences of nanoparticle fractions (Cu) ($0 \leq \emptyset \leq 3\%$) in the base fluid ($H_2O$), the intensity of the inlet velocity of the nanofluid and that of the rotational speed of the hexagonal cylinder as well as its rotation direction.

## 2. COMPUTATIONAL MODEL

### 2.1 Configuration

A descriptive diagram of the configuration studied is shown in Figure 1. The square vented cavity of dimension $L$ has four adiabatic and rigid non-slip walls. The diameter of the circle inscribed in the hexagonal cylinder occupying the middle of the cavity is $D$=0.25 L. The inlet and outlet ports' sizes $l$=0.2 L, are centered in the left and right vertical walls of the enclosure. The hexagonal cylinder is maintained at hot temperature $T_h$ and rotated with an angular velocity of $\omega$ (in both clockwise and counterclockwise rotation). The hexagonal rotation speed has been adjusted so that it is lower than the critical transition speed to avoid local turbulent motion. It should be noted that a positive value of $Re_\omega$ corresponds to the counter clockwise rotational direction. The cold nanofluid enters the cavity with a uniform velocity $U_{in}$ at a temperature $T_{inlet}=T_c(T_c<T_h)$. Gravitational acceleration acts in the negative direction of y.

### 2.2 Governing equations

In this study, the flow is assumed to be stationary. The nanofluid Cu-$H_2O$ inside the enclosure is supposed to be incompressible and Newtonian, while viscous dissipation effects are considered negligible. The nanoparticles are assumed to be in thermal equilibrium with the main liquid, i.e., they are homogeneous and well dispersed in the fluid and they are small enough to be considered as rigid spheres with constant diameter, which makes it possible to simplify the equations of the movement of fluids. The thermophysical properties of Cu nanoparticles and pure water are considered to be independent of the temperature, except for the buoyancy force density, where the Boussinesq approximation is adopted. The base fluid and nanoparticle properties are presented in Table 1.

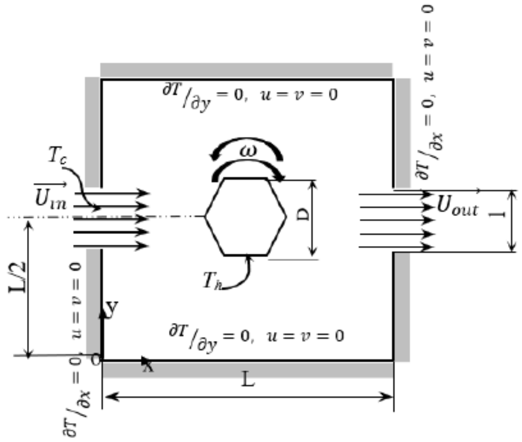


**Figure 1.** Schematic view of configuration

**Table 1.** Thermo-physical properties

| | **ρ** $[kg/m^3]$ | **c$_p$** $[J/(kg.K)]$ | **μ** $[kg/(m.s)]$ | **k** $[W/(m.K)]$ |
|---|---|---|---|---|
| $H_2O$ | 997,1 | 4179 | $10^{-3}$ | 0.613 |
| Cu | 8933 | 385 | --- | 400 |

The radiation effects are considered negligible. According to the above considerations, the flow and thermal fields inside the square enclosure with a rotating hexagonal cylinder are described by the following continuity, Navier–Stokes, and energy equations:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial y} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = -\frac{k_{nf}}{(\rho\, c_p)_{nf}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The following classical models are used to determine the effective thermo-physical properties of nanofluid:

Density

$$\rho_{nf} = (1-\emptyset)\,\rho_f + \emptyset\,\rho_s \tag{5}$$

Effective heat capacitance

$$\left(\rho\, c_p\right)_{nf} = (1-\emptyset)\left(\rho\, c_p\right)_f + \emptyset\left(\rho\, c_p\right)_s \tag{6}$$

Dynamic viscosity

$$\mu_{nf} = \mu_f(1-\emptyset)^{-2,5} \tag{7}$$

Effective thermal conductivity

$$k_{nf} = k_f\,\frac{(k_p+2\,k_f)-2\,\emptyset(k_f-k_p)}{(k_p+2\,k_f)+\emptyset(k_f-k_p)} \tag{8}$$

The Reynolds number is defined as

$$Re = \frac{\rho_{nf}\,U_{in}}{\mu_{nf}}D \tag{9}$$

Also, the rotational Reynolds number $(Re_\omega)$ is determined by

$$Re_\omega = \frac{\rho_{nf}\ \omega}{\mu_{nf}}\,D^2 \tag{10}$$

The average Nusselt number at hexagonal cylinder is calculated by:

$$Nu_{avg} = \frac{\bar{h}\,D}{k_{nf}} \tag{11}$$

### 2.3 Boundary conditions

The boundary conditions for this problem are:

- On the bottom and the upper walls:

$$u = 0, v = 0, \partial T/\partial y = 0 \tag{12a}$$

- On the left and the right walls:

$$u = 0, v = 0, \partial T/\partial x = 0 \tag{12b}$$

- On inlet port:

$$u = U_0, v = 0, T = T_c = 288\,K \tag{12c}$$

- On outlet port:

$$v = 0, \partial T/\partial x = 0 \tag{12d}$$

- On the hexagonal cylinder:

$$u = 0, v = 0, T = T_h = 323\,K \tag{12e}$$

## 3. NUMERICAL METHOD

To solve the governing equations systems of this problem, the SIMPLE algorithm and the second order scheme of the finite volume method [19] were used, and the calculations were made by the Ansys-Fluent 14.5 software.

### 3.1 Mesh independence

The triangular cell nested mesh is used for this study. The mesh is carefully designed to be refined in proximity to the hexagonal cylinder, gradually becoming coarser as it moves away from the hexagon (Figure 2). This strategy results in a reduction of overall computational cost while enhancing the accuracy of the simulation results. Four different meshes are chosen to analyse the effect of the nodes number on the solution of the case corresponding to $Re$=600, $Re_\omega$=-10 and $\emptyset$=3%. The variation of Nusselt number by varying the number of nodes is shown in Table 2. To have the lowest computation time with the best accuracy of the solution, this mesh of 277345 nodes is adopted for the calculations.

**Table 2.** Results of the independence study of the mesh at $Re$=600, $Re_\omega$=-10 and $\emptyset$=3%

| **Mesh** | 102365 | 152365 | 277345 | 389625 |
|---|---|---|---|---|
| **$Nu_{avg}$** | 17.44 | 22.91 | 23.5559 | 23.63 |

### 3.2 Code validation

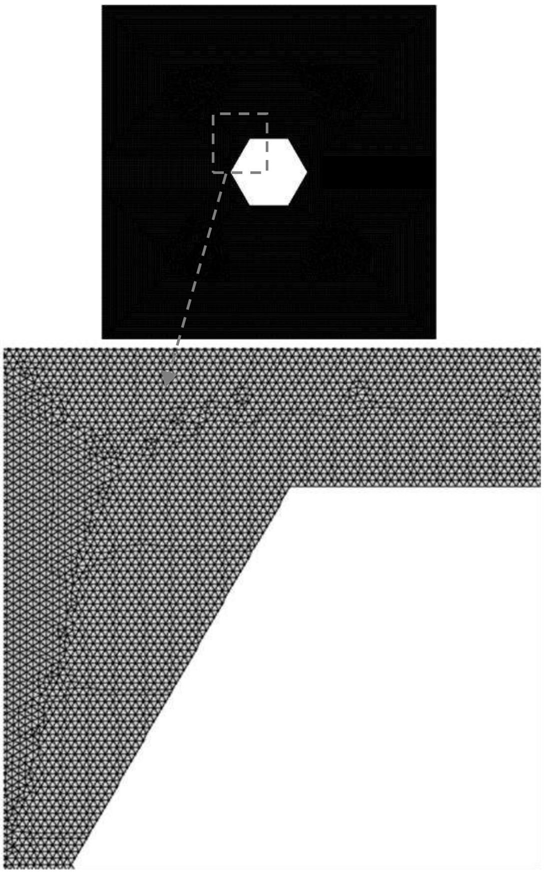


**Figure 2.** Close up view of mesh near the hexagonal cylinder

To validate the code which governs this simulation, a comparison was made between the Nusselt values obtained in this work and those which are calculated by the Churchill and Bernstein [20] correlation which corresponds to the cases of external flow around a cylinder with $Re\,\mathrm{Pr} \gtrsim 0.2$. Some values of this comparison are gathered in Table 3. The results are too compatible because they are in good convergence and the margin error is extremely minor.

The Churchill and Bernstein [20] correlation is given as:

$$Nu_{avg} = 0.3 + \frac{0.62\, Re^{1/2} Pr^{1/3}}{\left[1+(0.4/Pr)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5} \qquad (13)$$

**Table 3.** Comparison of the average Nusselt number calculated by this code and by Churchill correlation [20] for $Re_\omega$=0 and $Re$=200

| **Ø** | **0** | **0.01** | **0.02** | **0.03** |
|---|---|---|---|---|
| Nu [20] | 16.489 | 16.016 | 15.593 | 15.2056 |
| Nu (present work) | 15.66 | 15.50 | 15.334 | 15.18 |

## 4. RESULTS AND DISCUSSION

In this section, numerical results are presented in terms of average Nusselt number, stream function contours and isotherms, for a range of Reynolds number values (Re=200,400,600,800 and 1000), rotational Reynolds number ($Re_\omega$=±30,±20,±10,0) and nanoparticles volume fraction ($\emptyset = 0,\ 0.01,\ 0.02,\ 0.03$).

Figure 3 shows the effect of increasing nanoparticles volume fraction in the nanofluid ($\emptyset$) on the average Nusselt number for four values of the number of Re. First of all, for Reynolds numbers less than 1000, the Nusselt decreases with the increase $\emptyset$, this shows the dominance of the conduction process over convection. It is clear that the increase in $\emptyset$ has an ameliorating effect on the rate of transfer by forced convection only when the Re number of the laminar regime reaches the value of 1000. The figure also shows, that the average Nusselt number increases as Re increases, indicating that increasing the inlet speed of the nanofluid to the cavity enhances the forced convection transfer rate.

To examine the influence of the speed and the direction of the hexagonal cylinder rotation on the heat transfer rate inside the vented cavity the variation of the average Nusselt number as a function of the rotational Reynolds number is shown in Figure 4. It is clear that the direction of rotation (clockwise and counter clockwise direction) almost does not influence the heat transfer rate but the increase in the value of the angular velocity improves the heat transfer rate because the agitation of the particles near the hexagonal cylinder promotes the heat transfer between the hot hexagonal cylinder and the nanofluid. The lowest Nusselt value is, as expected, recorded when the cylinder is at rest because the conductive transfer is important in this case.

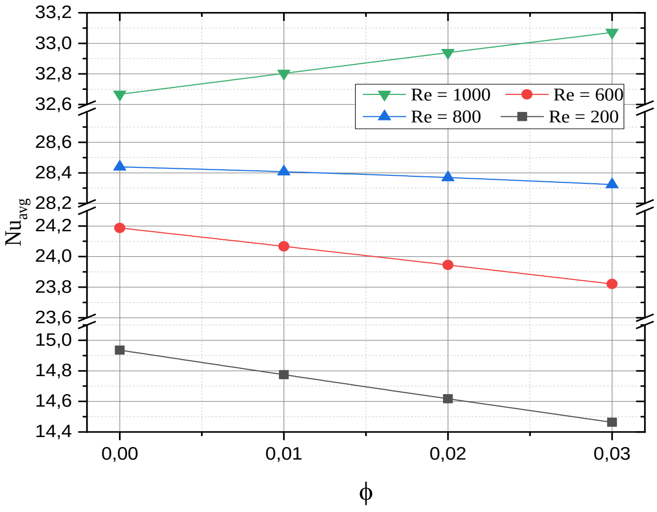


**Figure 3.** Variation of $Nu_{avg}$ with $\emptyset$ for four Re values and for $Re_\omega$=-30

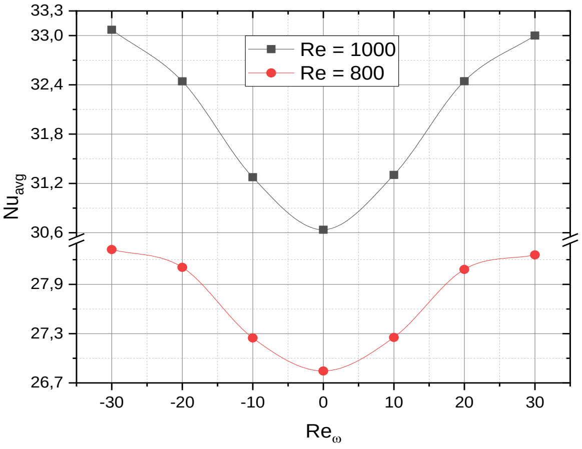


**Figure 4.** Variation of $Nu_{avg}$ with $Re_\omega$ for two $Re$ and for $\emptyset = 0.03$

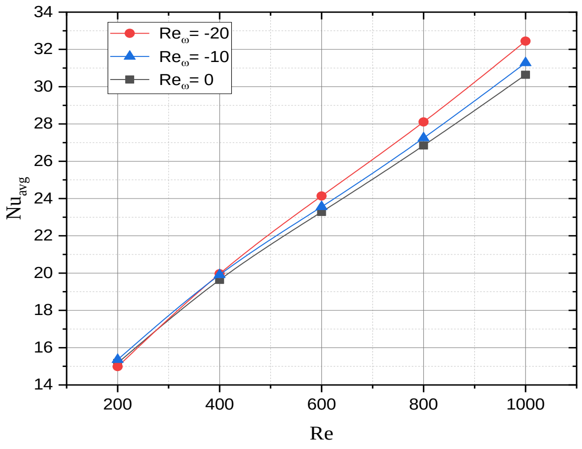
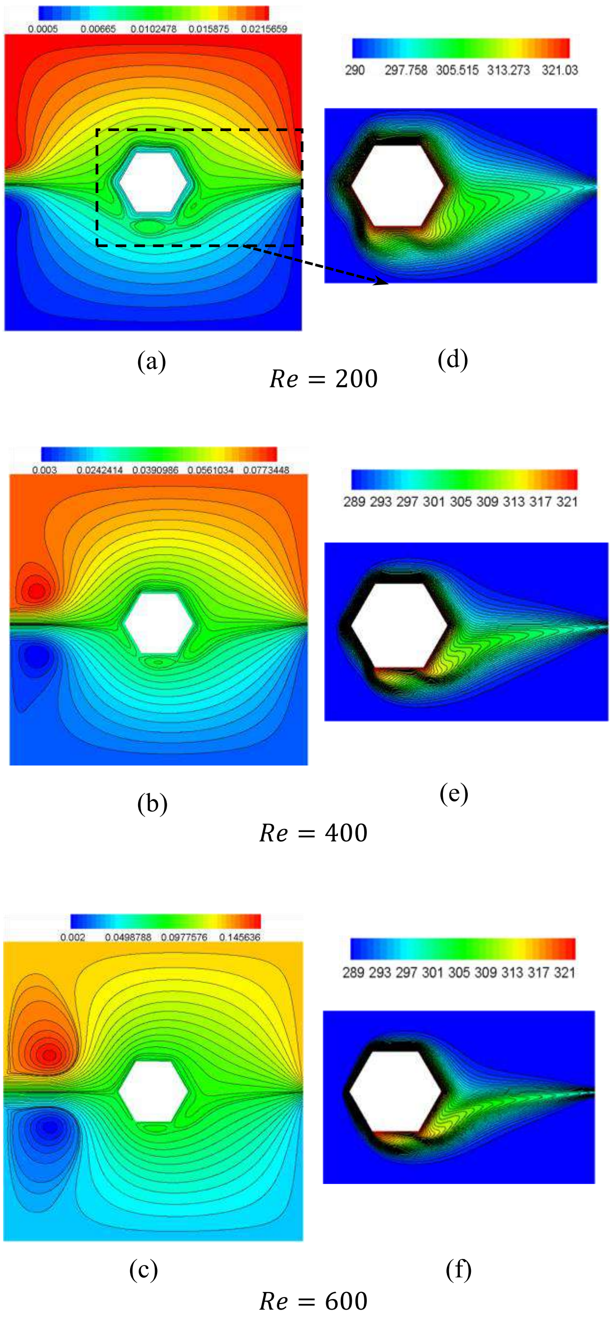


**Figure 5.** Variation of $Nu_{avg}$ with $Re$ for three values of $Re_\omega$ and for $\emptyset = 0.03$

Figure 5 also shows that the Nusselt number increases with increasing Reynolds number and also with increasing rotational Reynolds number, which means that the inlet velocity of the nanofluid into the vented cavity and the rotational velocity of the hexagonal cylinder increase the rate of heat transfer by forced convection in the vented cavity.

The streamlines and isotherms of some cases studied in this work are shown in Figure 6 and Figure 7. The depiction of isotherms focuses on the part of the cavity where the temperature change is substantial. This area, encompassing the hexagon and extending to the nanofluid exit, has been slightly magnified for better visibility. To examine the effect of nanofluid inlet velocity on the flow field and temperature distribution, Figure 6 shows the streamlines and isotherms inside the square cavity for 3 values of $Re$(200,400,600)and for $Re_\omega$=-20 that corresponds to a clockwise rotation of the hexagonal cylinder and for nanofluid with $\emptyset = 0.03$. It is shown that recirculation zones form in the vicinity of the inlet port, and these vortices increase in size with increasing Reynolds numbers (Figure 6 (a), (b) and (c)), which is explained by the intensification of forced convection. Rotating the hexagonal cylinder clockwise creates circulation vortices below the cylinder and with increasing Reynolds numbers this recirculation area becomes larger, making the forced convection effect more dominant. For isotherms, the color representation ranges from blue to red. The blue color represents the regions of low temperature, while red corresponds to high temperature. The hexagonal shaped cylinder in the center of the cavity acts as a heat source and results in the concentration of high temperature regions near its walls.



(a) (d)

$Re = 200$

(b) (e)

$Re = 400$

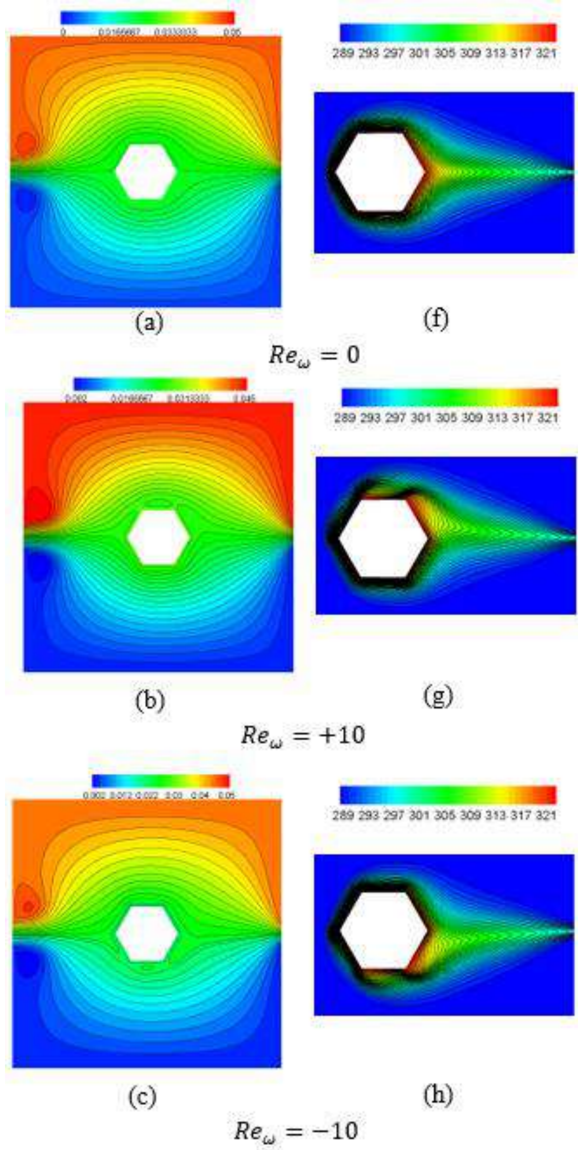
(c) (f)

$Re = 600$

**Figure 6.** Streamlines ((a), (b), (c)) and isotherms ((d), (e), (f)) for $\emptyset = 0.03$ and $Re_\omega$=-20

As long as the rotation of the hexagonal cylinder is clockwise ($\omega$<0), the isotherms tend to move downward, and with increasing the inlet velocity, they tighten more, which is due to the dominance of forced convection (Figure 6 (d), (e) and (f)).

Figure 7 presents the effects of increasing the rotational velocity and rotational direction of the hexagonal cylinder on the streamlines and on the isotherms respectively, inside the cavity. The streamlines are tighter around the cylinder for the higher rotational speed of the hexagonal cylinder (Figure 7 (d) and (e)), which means that the increase in the rotational velocity promotes heat transfer from the hot hexagonal cylinder to the nanofluid passing through the cavity. For a stationary cylinder ($Re_\omega$=0), the streamlines and the isotherms are almost symmetrical with respect to the line $y = L/2$ (Figure 7(a), 7(f)). It can be noticed that with the rotation of the cylinder counter-clockwise ($Re_\omega$=>0), the isotherms move upwards (Figure 7(g), 7(i)). By comparing the streamlines of Figures 7(a), 7(b) and 7(d) and those of Figures 7(c) and 7(e), we can see that rotating the cylinder in a clockwise direction causes vortices to appear under the cylinder but if the rotation is counter-clockwise, swirls appear above the cylinder. It has been observed that the rotation of the hexagonal shaped cylinder in a clockwise direction gives rise to the formation of vortices beneath the cylinder. Conversely, a counter-clockwise rotation leads to the generation of swirls above the cylinder. This dynamic phenomenon results in the manifestation of wavelike isotherms within the cavity. The magnitude of the heat transfer rate, which can be deduced from the isotherms, is influenced by both the velocity of the hexagonal shape's rotation and the inlet velocity of the Nano-fluid. Furthermore, the position of these heat transfer fluctuations is dependent on the direction of rotation. Moreover, the ventilation of the nanofluid within the cavity results in the extension of the isotherms towards the outlet port. This observation concords with the findings obtained from the analysis of the Nusselt number.



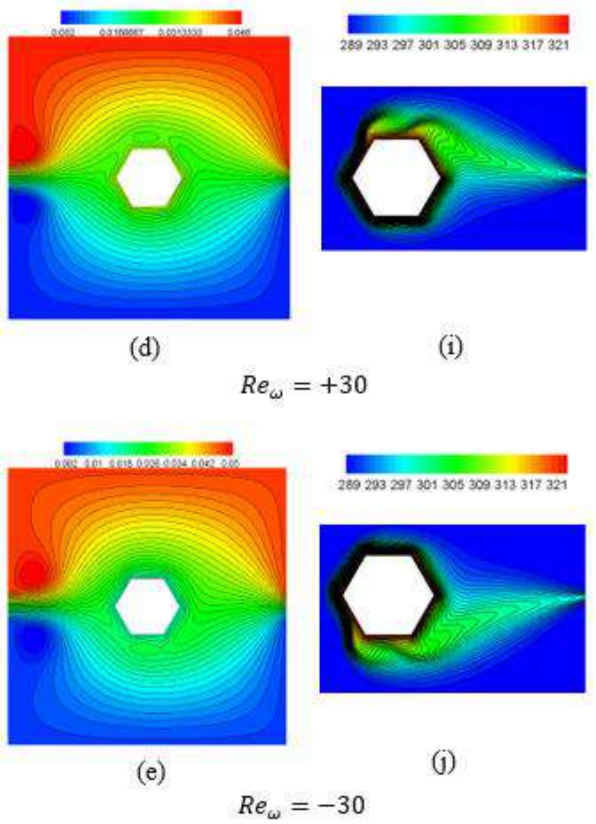


**Figure 7.** Streamlines ((a), (b), (c), (d), (e)) and isotherms ((f), (g), (h), (i), (j)) for $\emptyset = 0.03$ and *Re*=400

## 5. CONCLUSIONS

The heat transfer rate as well as the flow structures of a *Cu-H₂O* nanofluid cooling a vented square cavity were numerically investigated in this study. In the center of the cavity, a hexagonal heating cylinder rotates around its axis. The inlet velocity of the nanofluid is chosen such that the flow regime, which is assumed to be two-dimensional, remains laminar. The impacts of several parameters such as the Reynolds number, the volume fraction of the nanoparticles, the direction and the hexagonal cylinder angular velocity, on the hydro- thermal efficiency were analysed. The results showed that the heat exchange rate increases with increasing Reynolds numbers. In the case where the cylinder is stationary, an increase of 50% in the nanofluid inlet velocity leads to an increase of 18.56% in the rate of heat transfer. The lowest average Nusselt value is recorded when the cylinder is stationary and with increasing cylinder rotation speed the transfer rate increases. This growth is almost of the same magnitude in both directions of hexagonal cylinder rotation. An increase of about 50% in the rotational speed of the cylinder in either direction leads to a 4% increase in the rate of heat transfer. When the Reynolds number reaches the value of 1000, an increase of 1% in the volume fraction of the nanoparticles leads to an increase of 0.42% in the Nusselt number, i.e., an increase in the rate of heat transfer.

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## NOMENCLATURE

| | |
|---|---|
| $C_P$ | Specific heat, J. kg$^{-1}$. K$^{-1}$ |
| D | Distance between two opposite sides of the hexagon, m |
| h | Local heat transfer coefficient, W.m$^{-2}$.K$^{-1}$ |
| k | Thermal conductivity, W.m$^{-1}$. K$^{-1}$ |
| L | Square cavity side, m |
| Nu | Local Nusselt number along the heat source |
| Re | Reynolds number |
| $Re_{\omega}$ | Rotational Reynolds |

| | |
|---|---|
| T | Temperature, K |
| u | x-component of velocity vector, m. s$^{-1}$ |
| U | Velocity magnitude, m. s$^{-1}$ |
| v | y-component of velocity vector, m. s$^{-1}$ |
| x, y | x, y coordinates, m |

**Greek symbols**

| | |
|---|---|
| $\mu$ | Dynamic viscosity, kg. m$^{-1}$.s$^{-1}$ |
| $\emptyset$ | Nanoparticles volume fraction |
| $\rho$ | Density, kg.m$^{-3}$ |
| $\omega$ | Rotational velocity, s$^{-1}$ |

**Subscripts**

| | |
|---|---|
| avg | Average |
| f | Base fluid |
| in | Inlet |
| nf | Nanofluid |
| out | Outlet |