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RESEARCH ARTICLE

MIXED CONVECTION BETWEEN HOT AND COLD CYLINDERS IN SQUARE CHAMBER: STUDY THE DIRECTION AND VALUE OF THE ROTATIONAL SPEED

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ABSTRACT

This paper studies the heat transfer between two cylinders held in a square-shaped and thermally insulated chamber. The two cylinders rotate at constant speed. The right cylinder has a hot wall the left one is cold. The chamber is filled with water (Pr = 6.01) for the purpose of transferring heat between the two cylinders. The heat pattern used in this research is convective and mixed, so the values of the studied Richardson number are limited between 0 and 1. The speed of rotation of the cylinders is expressed by Re number. The experiment was carried out in numerical way based on the finite-volume method used in principle by ANSYS-CFX. The points studied here are the speed and the direction of rotation of the cylinders; and the intensity of thermal buoyancy force. The results of the work showed that the direction of the rotation of the cylinders has a strong influence on the quality of heat transfer, especially when the thermal pattern is mixed.

KEYWORDS

thermal transfer, rotational cylinder, mixed convection, numerical simulation, heat exchangers.

1. Introduction

Recently, a significant group of research has been devoted to study of heat exchangers in order to increase their efficiency. While the heat exchangers are a must in many fields of industry and engineering, notably mining, electrical energy production centers, production of cosmetic and pharmaceutical products and so on. Previous research in this field touched the quality of the fluid used, the geometry of the heat exchanger and the type of heat transfer used. A group researchers performed a numerical work on the heat transfer and fluid mechanics in square chamber (Mishra et al., 2017). The chamber was considered to be opened with two ports, one for inlet flow and the second for the outlet. The heat transfer was studied between the walls of the cylinders, which are hot and the fluid flow that is cold. The results showed that the arrangement of the cylinders significantly influenced on the heat transfer. Some researcher also studied the mixed convection in square chamber (Selimefendigil and Oztop, 2015).

The chamber is perfectly ventilated with two ports. The simulations are performed in unsteady regime. Some new geometrical modifications are done in order to improve the heat transfer. This research are also done for the case of studying the heat transfer in ventilated chamber of square cross-section (Sourtiji et al., 2014; Karbasifar et al., 2018; Mamun et al., 2010). Numerically studied the mixed convection between two rotating cylinders of concentric arrangement. Both cylinders were considered to be rotated (Laidoudi and Ameur, 2020). The direction of rotation of the cylinders and the value of rotation were the studied parameters. It was concluded that the direction of rotation of both cylinders significantly influence on the heat transfer between the concentric cylinders.

The heat transfer in annular spaces is of three types: if the heat is the main cause of the fluid movement, then this type is called natural convection heat transfer (Laidoudi, 2020; Guendouci et al., 2021; Yigit and Chakraborty, 2017; Bouzerzour et al., 2020). But if the heat transfer is due to the rotation of the cylinders or the presence of internal flow, this type is called the forced convection heat transfer such as (Laidoudi and Makinde, 2020; F. Selimefendigil and Öztop 2014; Panda and Chhabra, 2011; Hussain et al., 2019; Sheikholeslami et al., 2016). Both types of heat transfer in one system give the mixed convection such as (Tasnim and Mahmud 2002; Amoura et al., 2006; Teimouri et al., 2017; Srinivasacharya and Shafeeurrahman, 2017; Hekmat and Ziarati, 2019).

(Dawood et al., 2015) represented a review on the enhancement of convection heat transfer in annular spaces. The natural forced and mixed types are treated here. The work showed the influences of different parameters on the quality of thermal transfer. A studied the natural convection of elliptical cylinder which is horizontally confined in circular cylinder (Tayebi et al., 2019). The study tested geometrical and operational conditions on the heat transfer. A studied the natural and mixed convection of different hot and cold cylinders in adiabatic enclosure (Garoosi and Hoseininejad, 2016). The nanofluids were used as working fluid. Therefore, the concentration of nanoparticles and their size were the studied parameters in this study.

By reviewing previous research, it should be noted that there are no extensive results related to the study of heat transfer between a hot and cold cylinder, especially since the cylinders rotate at constant speeds. Therefore, this work aims to present some results related to the effect of rotational speed and the value of two cylinders confined inside a square chamber, the first is hot and the second is cold. Free and forced convections heat transfers are combined in this work to give a mixed convection.

2. Studied Domain, Mathematical Formulations and Boundary Conditions

The studied system is represented in a simplified form in Figure 1. The system consists mainly of two cylinders, one hot and the other cold, immersed in a thermally insulated chamber and completely filled with

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thermal medium (water). Both cylinders have the diameter (d) and the chamber has the dimension (H). The ratio d/H = 0.25 of the system. The right cylinder has a hot surface (T_h) and the left cylinder has a cold surface (T_c). The cylinders rotate inside the chamber at a constant speed and in different directions. This work aims to understand the effect of the speed and direction of rotation of the cylinders on the heat transfer between the two cylinders. The effect and the absence of thermal buoyancy are experimented in this work. Two cases of the direction of rotation of the cylinders are tested in this work.

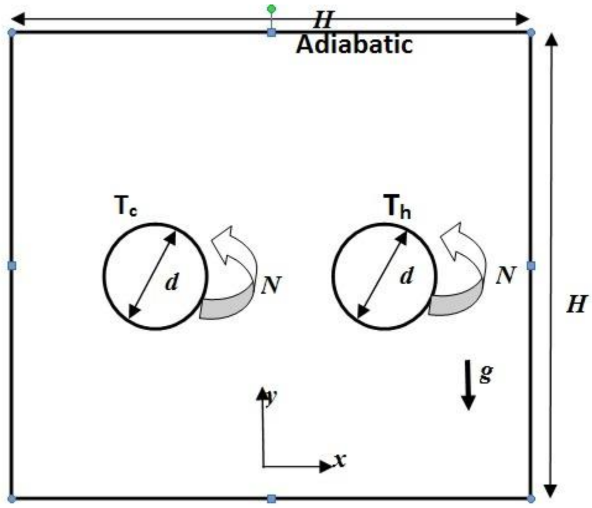

Figure 1: Representation of studied domain.

The basic equations that allow simulation of the fluid with heat transfer are:

Continuity equation

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

Momentum equations

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

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ri\theta \quad (3)$$

Energy equation

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{PrRe}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \quad (4)$$

All parameters in above equations are non-dimensional. Their dimensional values are determined as follows:

$$(U,V)=\frac{(u,v)}{N\times d},P=\frac{p}{\rho(N\times d)^2},\theta=\frac{(T-T_c)}{T_h-T_c} \quad (5)$$

$$(X,Y)=\frac{(x,y)}{d} \quad (6)$$

$$Re=\frac{\rho(Nd^2)}{\mu},Pr=\frac{\mu C_p}{k},Ri=\frac{g\beta_T\Delta Td}{(N\times d)^2} \quad (7)$$

The Reynolds number (Re) describe the rotational speed of the cylinder, the Prandtl number (Pr) describe the thermo-physical characteristics of the working fluid and the Richardson number (Ri) controls the value of thermal buoyancy force.

The local and average values of the Nusselt number are calculated as follows:

$$Nu_L=\left(\frac{\partial \theta}{\partial n}\right)_{wall} \quad Nu=\frac{1}{A}\int_s Nu_L dA \quad (8)$$

The boundary conditions were used for the present simulations are:

- The right cylinder is supposed to be hot (Th) and rotating.
- The left cylinder is assumed to be cold (Tc) and rotating, too.
- The outer chamber is adiabatic.
- Note. No-slip boundary layer is adopted near all walls of the geometry.

3. Numerical Procedure and Validation Test

For the sake of brevity in this section, the numerical methods used in solving differential equations are the same as those used in previous works and (Laidoudi, 2020; Laidoudi and Makinde, 2020). Also, this research include a validation test that proves the ability of this methodology in reaching correct and significant results (Laidoudi and Makinde, 2020; Guendouci et al., 2021). This section also contains grid independency test where the number of grid elements is tested to be efficient for the determination of satisfactory results. Figure 2 shows an image of the mesh used to solve the governing equations. Indeed, the elements have a triangular form with concentration near the inner cylinders where the thermal and flow layers are sensitive. The grid independency test was done by creating grids with different numbers of elements so that each time the number of grid element is doubled and then the value of Nusselt number is calculated each time. When the difference in Nusselt number value becomes negligible then it can be considered that the number of grid elements is sufficient to reach the correct results. Indeed, Table 1 show the numbers of grid elements and their results of a simulation for Re = 5, Ri = 0 and Pr = 6.01. The results of this test prove that the mesh (M3) is really satisfactory.

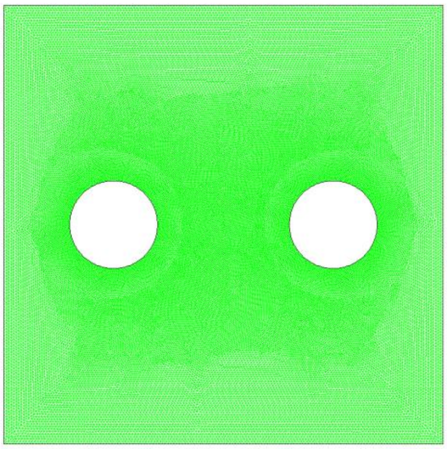

Figure 2: Mesh of the studied geometry.

Table 1: Grid independency test

Mesh	Number of elements	Nu	Variation (%)
M1	12000	2.23267	2.21
M2	24000	2.18320	0.089
M3	48800	2.18124	-

4. Results and Discussion

We mention here that this work studies the heat transfer between two cylinders rotating at a constant speed, the first (the right cylinder) is hot and the second (the left cylinder) is cold. The two cylinders are placed horizontally in a thermally insulated chamber. Water is the heat medium used in this work of Prandtl number (6.01). The fluid movement resulting from the rotation of the cylinders is expressed in terms of studied Reynolds number between the values 10 and 40. Richardson number describes the intensity of buoyancy force; in the present research the value of Ri is chosen between 0 to 1. Based on the direction of rotation of the cylinders, the results of this work are divided into two cases.

Case N1: the cylinders rotate in one direction in the positive direction

The positive direction is upward. Figure 3 represents the fluid pattern inside the container in terms of the change of Reynolds and Richardson numbers. The friction of the fluid with walls of the rotating cylinders produced a circular flow inside the chamber as the center of this flow is located in the center of the container between the two cylinders. Also, the circular motion of the fluid and the direction of its rotation created two small opposite vortices, on in the upper right and the other in the lower left. The size of those vortices increases gradually with increasing the value of Re and/or Ri. In general, it is noted that the velocity of the fluid in the container increases with the increase in the speed of rotation of the cylinders. Also, the effect of the value of Richardson number on the movement of the fluid is almost small.

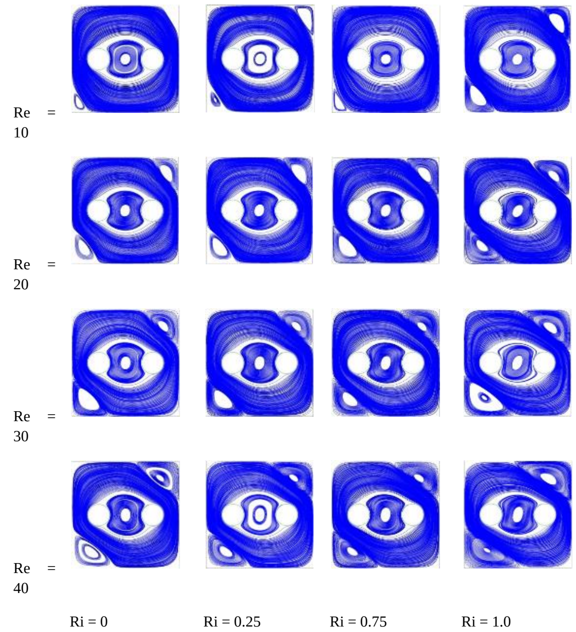

Figure 3: Streamlines for the first case for different values of Re and Ri.

Figure 4 shows the heat distribution (isotherms) inside the room in terms of Re and Ri values. Note that the heat distribution follows the direction of the fluid movement. It is also noted that the direction of rotation of the cylinders completely helps in the direction of thermal buoyancy effect and this helps in the process of heat transfer between the hot and cold poles. Through this thermal distribution, it can be seen that the thermal condensation (temperature gradient) around the two cylinders gradually increases with increasing rotational speed (increasing the value of Re), and this indicates that the heat transfer increases in this case. On other hand, the effect of Ri on the heat distribution is almost negligible in this first case of rotation.

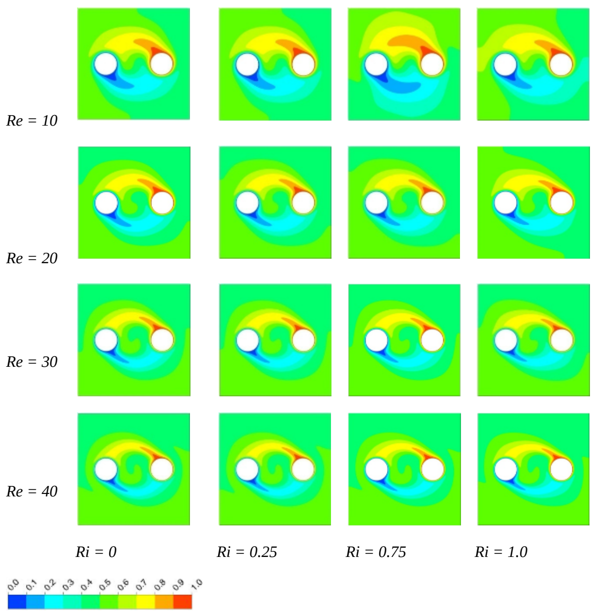

Figure 4: Isotherms for the first case for different values of Re and Ri.

Figure 5 shows the variation of the average value of Nu in terms of Re and Ri of the hot cylinder (the right one). As it was previously deduced, the increase in Re number increases the values of Nu. On other hand, there is no change in the values of Nusselt number relative to the Richardson number. From here we can conclude that the heat transfer between the two cylinders increase with increasing rotational speed and there is no significant effect of thermal buoyancy force in this case. Indeed, this first case is helpful for cooling applications.

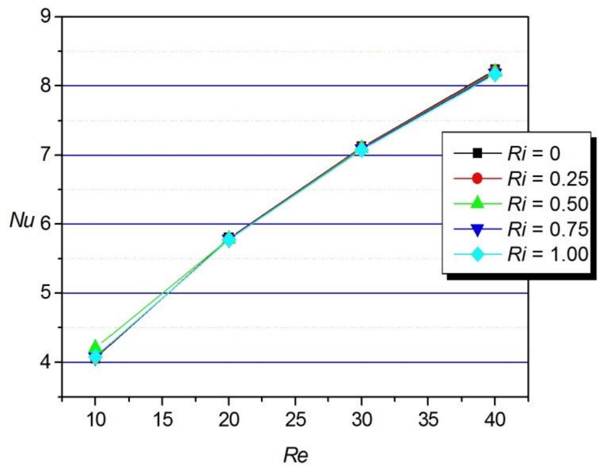

Figure 5: Variation of average Nu number as function of Re and Ri for positive direction.

Case N2: the cylinders rotate in one direction in the negative direction

In this case, the cylinders rotate in the negative direction (downwardly) which is the opposite of thermal buoyancy effect. Figure 6 shows the structure of the flow inside the chamber as a result of the reverse rotation of the cylinders, as well as the effect of thermal buoyancy. Like the first case, the rotation of cylinders also produced a circular flow except in the opposite direction to the first case with small secondary eddies at the angles corresponding to the angles in the first case.

In contrast to the first case, the effect of thermal buoyancy on the movement of the fluid is very clear. This is evident in all of the following:

- Lack of organization in the structure of the flow in terms of Ri values;
- Suppression of the secondary vortices in some cases of Ri and Re;
- Bend and disappearance of the main vortex center between the two cylinders in some cases.

In some cases, it is observed that the flow has difficulty I am travelling, which creates secondary flows. This effect is the result of the opposite of flow movement resulting from the rotation of the cylinder and the opposite direction of the effect of thermal buoyancy force.

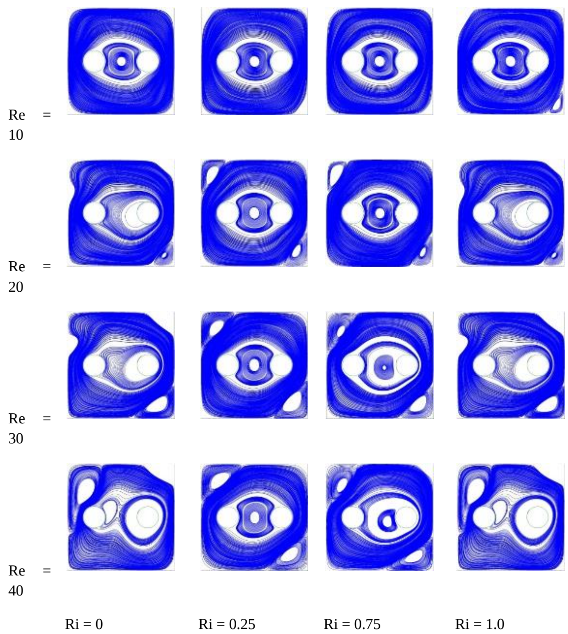

Figure 6: Streamlines for the second case (negative direction) for different values of Re and Ri.

Figure 7 shows the dimensionless temperature (isotherms) in the chamber in terms of the studied values of Ri and Re for this second case where the direction of the cylinders is negative, and it is opposite to the direction of thermal buoyancy force. Through the figure, it is clear that as a result of the reverse rotation of the cylinders, the hot flow became in the lower direction and the cold flow in the upper direction. Also, the temperature gradient around the cylinders increases gradually with increasing Re number only for the case of Ri = 0 and Ri = 0.25. This shows that the heat transfer decreases in residual states for the residual values of Ri number.

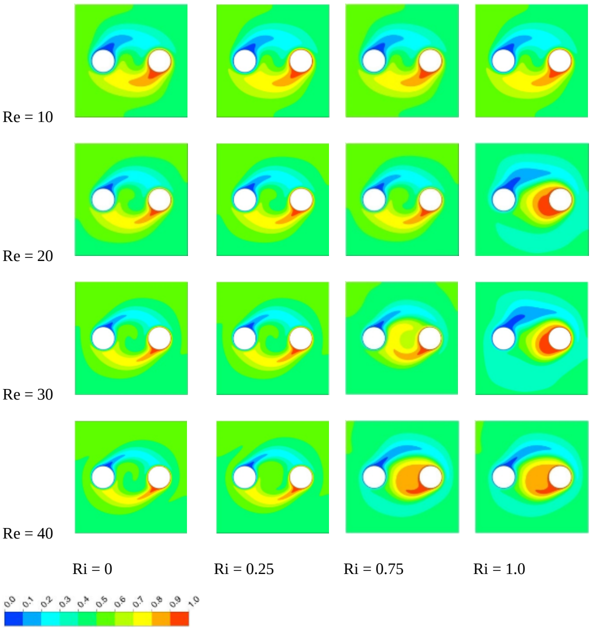

Figure 7: Isotherms for the second case (negative direction) for different values of Re and Ri.

Figure 8 shows the values of Nu versus Re and Ri for the hot cylinder. It is clear that for Ri = 0 and 0.25 the increase of the value of Re increases the value of Nu. On other hand, for Ri = 0.5, 0.75 and 1, increase of Re affects negatively on the value of Nu. This condition can be applied in the applications aimed at thermal insulation of warm elements.

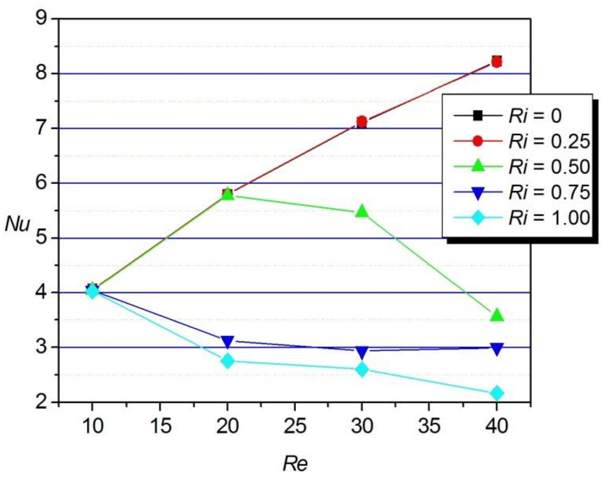

Figure 8: Variation of average Nu number as function of Re and Ri for negative direction.

5. Conclusion

This work was carried out for the purpose of studying the effect of rotational direction of the cylinders on the quality of heat transfer. The studied domain consists of a closed chamber and filled with a liquid (water). Inside this chamber there are two cylinders, one hot and the other cold. Both cylinders rotate. Since there is a heat transfer between the two cylinders, we decided through this work to study the speed and the direction of the two cylinders on the heat transfer. Two cases have been achieved, the first of the two cylinders rotate upwards as the thermal buoyancy effect, and the second is opposite to the thermal buoyancy effect. The results showed the following points:

- The first case helps improve heat transfer, making it suitable for refrigeration fields.
- The second case, with the presence of thermal buoyancy, is suitable for thermal insulation cases of hot elements.
- The flow inside the chamber is more stable in the first case.

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