Numerical Investigation of Heat Transfer Enhancement of Double Pipe heat exchanger

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Abstract. The double pipe heat exchanger type has low heat transfer rate compared with other types of heat exchangers. Therefore, this article aims to enhance the heat transfer rate of that type of heat exchanger by introducing a rotation of the exchanger inner pipe combined with changing the pipes eccentricity. Three dimensional, steady state, and incompressible CFD model was constructed for investigation of the effect of rotation and eccentricity on the heat transfer rate. A double pipe heat exchanger which was used for this study consists an inner pipe and an outer pipe of diameter 50 mm and 150 mm respectively with a length of 2000 mm. The inner pipe is assumed to rotate at a variable speed of 0, 100, 200, 300, 400 and 500 rpm and the eccentricity of the inner pipe is changed from 0.0 to 40 mm from the center of the outer pipe. The results showed a significant enhancement in the heat transfer rate due to the eccentricity change and the inner tube rotation. However, the pressure loss through the heat exchanger increases with the increase in the rotational speed of inner pipe.

Keywords: Heat and Mass Transfer, heat Exchangers, Modeling

1 Introduction

Techniques for heat transfer augmentation are relevant to several engineering applications. In recent years, the high cost of energy and material has resulted in an increased effort aimed to produce more efficient heat exchange equipment [1]. Furthermore, there is a need for miniaturization of heat exchangers in specific applications, such as space and vehicle applications, through the augmentation of heat transfer rate [2]. There are few techniques for heat transfer augmentation without significant effects the overall performance of the system [3], [4], [5]. There are three types of heat transfer augmentation techniques, passive, active and combined type [6]. Passive techniques generally use surface or geometrical modifications to the flow channel by incorporating inserts, additional devices or surface treatment which promotes higher heat transfer coefficients by disturbing the existing flow behavior and they do not require any external power input. Active techniques are more complex than passive techniques because they require some external power input to cause the desired flow modification and improvement in the rate of heat transfer such rotating bodies, electric field, acoustic or surface vibration etc.[7]. A compound augmentation technique is the one where more than one of the above-mentioned techniques is used in combination with the purpose of further improving the thermo-hydraulic performance of a heat exchanger [8]. The majority of commercially interesting enhancement techniques are currently limited to passive techniques because of their low cost and easy handling. The lack of use of the active techniques is related to the cost, noise, safety, or reliability concerns associated with the enhancement device [4].

Murata and Iwamoto [9] investigated numerically the effect of inner-wall rotation on heat transfer in cylindrical flow-passages. They observed that spiral vortices appeared in the downstream region when the rotation speed of the inner-wall increased that was because of centrifugal force formed by rotation. They found that rotation enhances the heat transfer rate. Yazıcı et al. [10] studied experimentally the paraffin melting behavior through a horizontal double tube heat exchanger for both the concentric and eccentric of the inner tube. They changed the eccentricity of the inner pipe from the center of the outer one three times and compared the results with the concentric geometry. At the maximum eccentricity, the total melting time reduced compared to the concentric one. Abou-Ziyan et al. [11] presented the effect of fins and rotating of concentric inner pipe of double pipe heat exchanger on heat transfer and pressure drop. They made a compression between the results of inner plain and finned pipe under stationary and rotating conditions.

They set up experiments for one plain pipe and three finned pipes with variable helical fin spacing at different rotating speeds. He investigated that the maximum rotating speed enhanced the Nusselt number and also improved the ratio of heat exchange to pumping power. El-Maghlany et al. [12] studied experimentally the performance of counter-flow in horizontal double tube heat exchanger after adding Cu-nanoparticles to the water in the annulus of the heat exchanger. They rotated the inner tube which contained the hot water at variable speeds while the outer pipe was stationary. Their results showed that rotation enhancement the rate of heat transfer as a result; the heat exchanger effectiveness and the transfer number units (NTU) improved and increase the pressure drop. Nobari and Nekoubin [13] studied the effect of inward and outward eccentricity on incompressible fluid flow in a curved annulus heat exchanger. They studied the effects of the dimensionless parameters such as the Dean Number, Reynolds number, curvature ratio, aspect ratio, and eccentricity on the flow performance and friction factor. Their results showed that the outward eccentricity caused a deformation in the secondary flows and axial velocity profiles. Otherwise, the friction factor reduced as the eccentricity increases due to the secondary flow intensity decreased. Dhaidan et al. [14] investigated experimentally and numerically melting of nano-enhanced phase change materials (NePCM) in an annular area between two circular cylinders. They exhibited a constant heat flux to the inner cylindrical tube, on the other hand, they insulated the outer shell thermally. They studied the impact of eccentricity by lowering the center of the inside heated tube and they found that the higher melting rate and temperatures are at the upper part of the capsule due to natural convection. They also found that the melting rate of NePCM can be increased by using an eccentric shell by lowering the center of an internal cylinder or by increasing the tube area. Wu et al. [15] studied the effect of porous media on the natural convection for the temperature dependent viscosity of fluids inside annulus between two vertically eccentric spherical. They calculated Nusselt numbers for a different range of Raleigh number, the outer sphere eccentricity, porosity of the media and Darcy number. Their results showed that maximum value of Nusselt number increase with an increase in Prandtl number for both positive and negative eccentricity and that have a better effect of convection heat transfer compared to the concentric case. From the previous studies, it is found that there were rare researches on a combination of eccentricity and rotation. Therefore, the scope of the present study is concerned with the enhancement of the double pipe heat exchanger performance through changing the eccentricity of the inner pipe center as well as the supplementary turbulence due to the inner tube rotation. To achieve these aims, a numerical model was constructed in order to investigate the effect of rotational speed of the inner pipe with different eccentricity ratio on the heat transfer coefficient.

2 Numerical setup

In this research, a three-dimensional, steady, incompressible and turbulent model was created to investigate the effect of inner pipe rotation on the heat transfer rate at different eccentricity. The physical properties of the fluid within the computational domain are assumed to be constant without changing its phase. This numerical model was built up using ANSYS Fuelnt 16.0 and is based on the following governing conservation equations.

Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho u_i) = 0 \qquad (1)$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P_i}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j} + \rho u_i u_j\right) \qquad (2)$$

Energy equation:

$$\frac{\partial(\rho T)}{\partial x_i} + \frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{K}{C_p}\frac{(\partial T)}{\partial x_i}\right) \qquad (3)$$

2.1 Physical domain

The physical model consists of a double pipe heat exchanger with an inner pipe and an outer pipe of diameter 50 mm and 150 mm respectively and its length is 2000 mm. An extension of 1000 mm was added to the original domain length as illustrated in Figure 1. In order to eliminate the reverse flow which is resulted from the induced centrifugal force by flow rotation where a low-pressure zone generated adjacent to the exit boundary. Different computational domains were created according to the pipes eccentricity. The eccentricity of the inner pipe center relative to the outer pipe center was taken in this study ε = 0, 20, 30 and 40 mm.

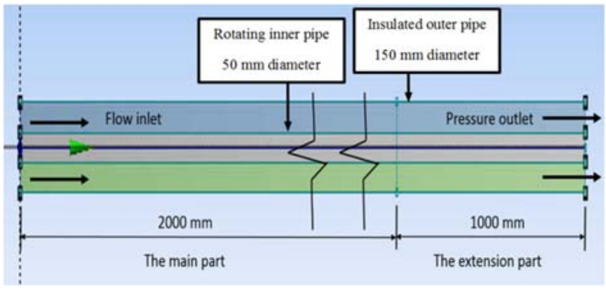

Fig. 1. The physical model

2.2 Boundary conditions

The inner fluid was assumed in a phase change mode (condensation) that means the inner pipe surface temperature remains constant and it was assumed to be 90° C. The annular flow inlet temperature was assumed to be at 25 °C and the outlet pressure was atmospheric. Fluids were used in this study were water. The annular flow inlet velocity was proposed to be 0.05, 0.1, 0.2, 0.35 and 0.5 m/s. The inner pipe of the heat exchanger rotated with a variable speed of 0, 100, 200, 300, 400 and 500 rpm while the outer pipe was kept stationary and adiabatic. The copper is selected for inner pipe material because of its high thermal conductivity.

2.3 Mesh independence study

A structured grid with hexahedral cells which gives considerable computational advantages is used at the annulus region as illustrated in Figure 2. A two different sizing were selected which are 75000 and 145000 cells. Temperature distribution along the heat exchanger of these grid systems was compared together for the purpose of mesh independence as shown in Figure 3. It was found that a grid sizing of 145000 elements is sufficient to capture all the gradients that occurred in the flow domain.

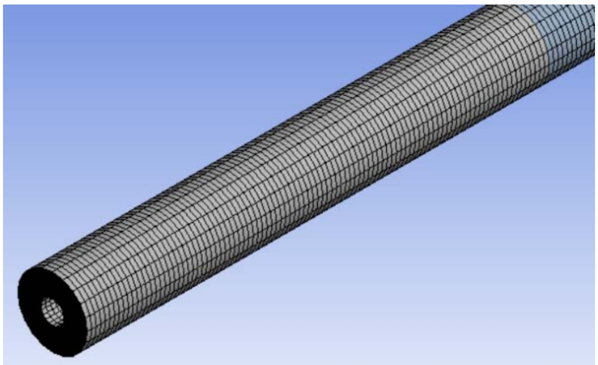

Fig. 2. The computational Domain

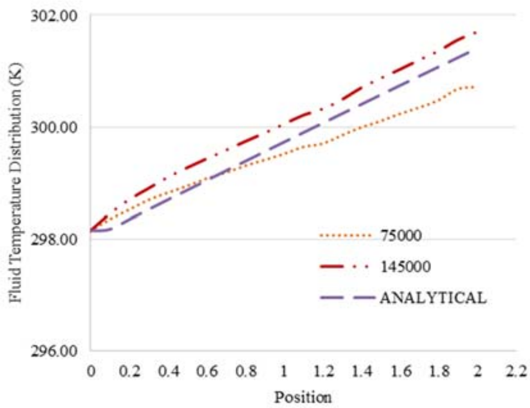

Fig. 3. Grid independence verification

2.4 Numerical model validation

To check that the numerical model meets specifications and fulfills its intended purpose of the double pipe heat exchanger, mathematical equations were used to calculate outlet temperature of the cold fluid, heat transfer rate, Nusselt number and pressure drop for the cases of centric pipe with variable axial velocity. The Reynolds number (Re) is calculated and used to characterize different flow regimes of the same fluid, such as laminar or turbulent flow. For laminar flows, Nusselt number approach to one and that refers to similar values of convection and conduction. For turbulent flow, convection is larger than conduction heat transfer leading to larger Nusselt number up to 1000. In the heat exchanger, the loss of heat transfer rate from the hot surface is equal to the gain of heat transfer rate to the cold fluid.

$$Q = A_S\, h\, T_{mean} = m_c\, cp\, (T_{out} - T_{in}) \quad (4)$$

The pressure drop due to friction between the annular fluid and both inner and outer pipe due to fluid viscosity is calculated by the following equation:

$$dP = \frac{f\, L}{2\, g\, D_h} V^2 \quad (5)$$

The results of analytical equations were used to validate the numerical model results. Analytical results and numerical results of Nusselt number are shown in Figure 4 while the results of pressure drop caused by fluid friction through the pipe are shown in Figure 5. It is clear from these figures that there is a good agreement between the numerical and analytical results.

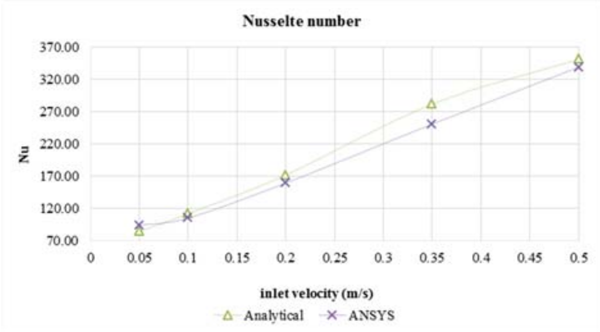

Fig. 4. Numerical model and analytical Nusselt number comparison

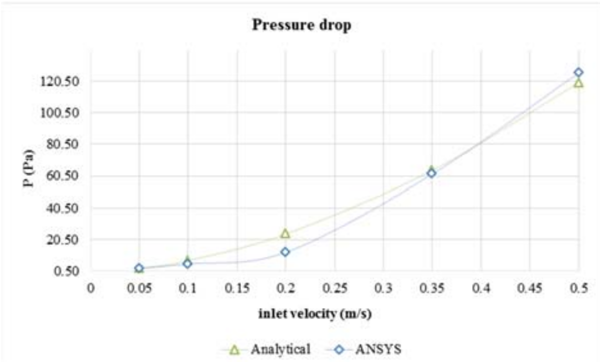

Fig. 5. numerical model and analytical Fluid pressure drop comparison

3 Results and discussion

The main indicator of heat exchanger performance enhancement is Nusselt number. The higher the fluid Nusselt number, the higher performance of the heat exchanger. The strongest parameter influence on convection heat transfer is a fluid rotational speed which increases the turbulence of the annular fluid. As a result, the heat transfer increases. Rotation of inner pipe has a positive effect on Nusselt number as shown in Figure 6. As rotational speed increased by 300%, Nusselt number increased by 182% while increasing the inlet velocity by the same rate, Nusselt number increased by 70%. Heat transfer rate is also affected by rotational speed more than Reynolds number.

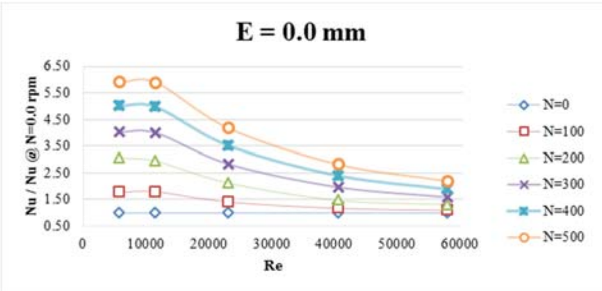

Fig. 6. Rotation speed effect on Nusselt number ratio of centric pipe

Figure 7 shows stream line at the same inlet velocity with a different rotation speed of concentric inner pipe. As rotation increases the velocity magnitude increases that means more turbulence leads to an improvment in the heat transfer.

The effect of changing the eccentricity of the inner pipe on Nusselt number comparing with concentric one is illustrated in Figure 8. 40 mm eccentricity is the most modes in Nusselt number augmentation. Stream lines with inner pipe rotational speed of 500 at different eccentricity is given in Figure 9. The results showed that, the increase in the eccentricity leads to growing in the magnitude of velocity. At an eccentricity of 40 mm, there are two generated vortices that means more turbulence and so an improving in the heat transfer. The generated vortex in the large gap aids to mix the hot fluid near the hot inner pipe with the cold one near the outer pipe at the large gap.

The fluid pressure drop across the heat exchanger has been negatively affected by fluid Reynolds number and rotation of the inner pipe. As the Reynolds number and rotational speed increase, pressure drop increase sequentially. Effect of inner pipe rotation speed on pressure drop is remarkable at low Reynolds number compared to high Reynolds number where it is illustrated in Figure 10.

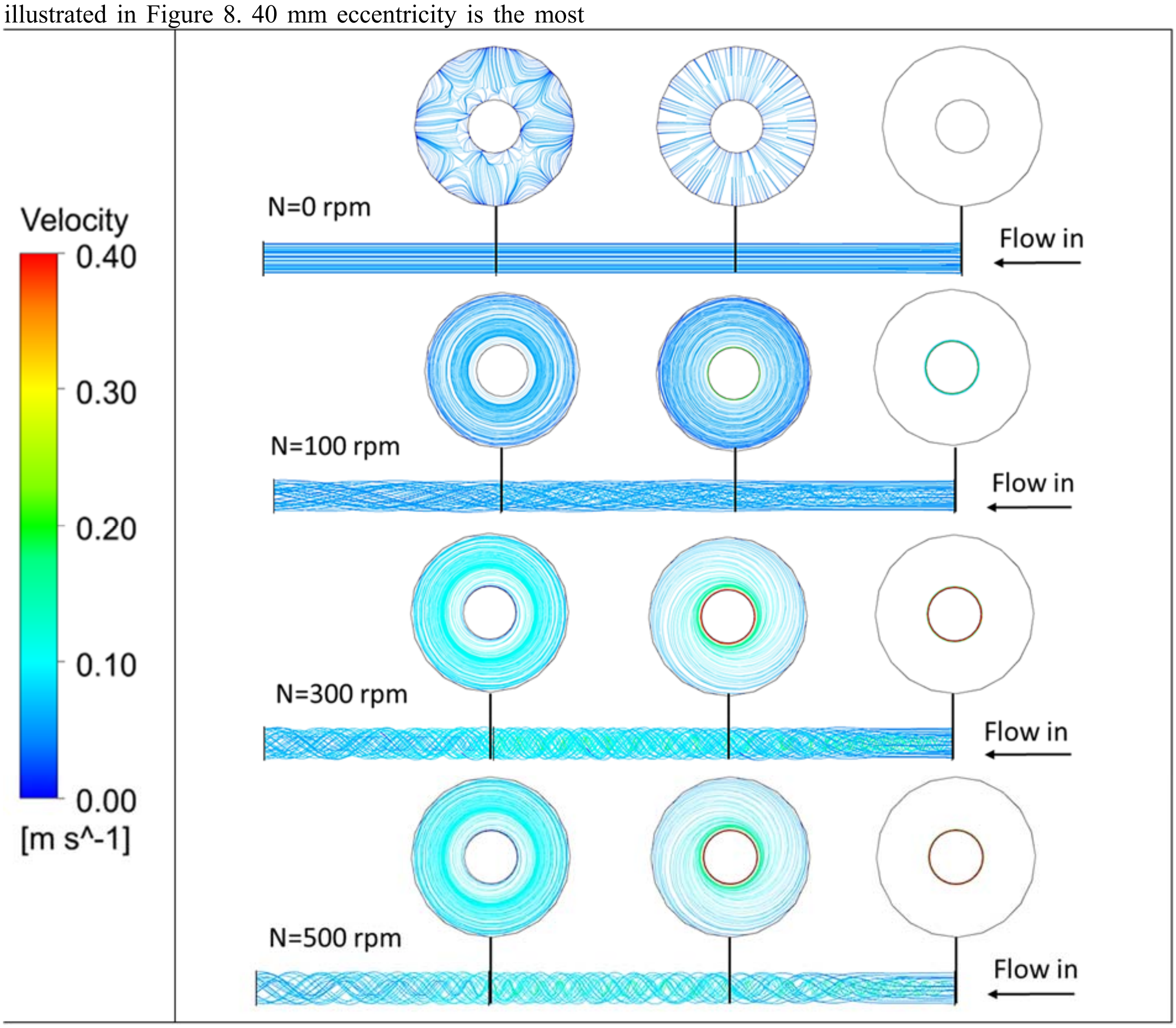

Fig. 7. Streamlines colored by velocity magnitude of centric pipe at different rotation speeds

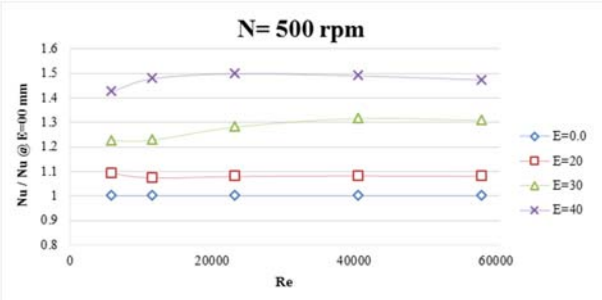

Fig. 8: Eccentricity effect on Nusselt number ratio of rotating inner pipe at 500 rpm

As the rotational speed increases, more inlet pressure is needed to overcome the pressure drop due to rotation. This rotation increases the friction of fluid on the inner pipe and outer pipe surfaces. The impact of increasing the eccentricity on pressure drop is illustrated in Figure 11. The eccentricity of 30 and 40 mm increase pressure drop than the eccentricity of 20 mm due to the decrease in the gap width.

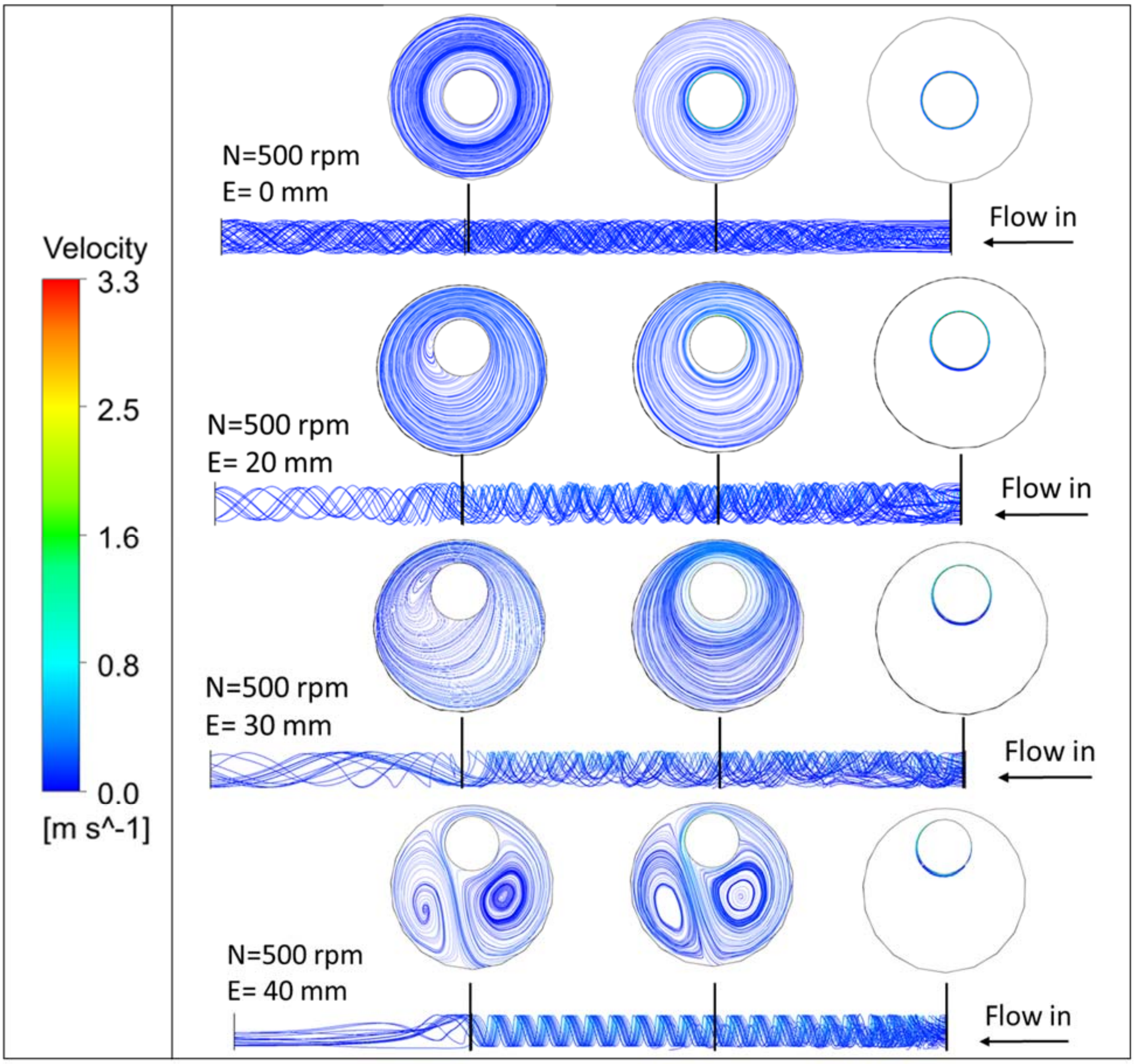

Fig. 9. Streamlines colored by velocity magnitude at different eccentricity of rotating inner pipe at 500 rpm

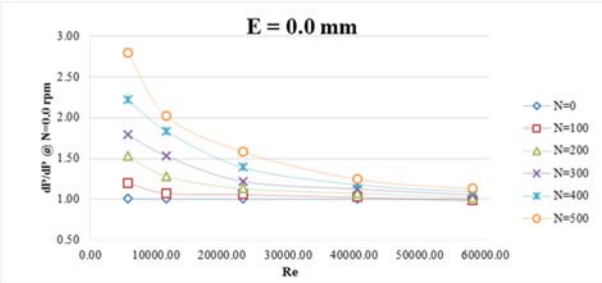

Fig. 10. Rotation speed effect on pressure drop ratio of centric pipe

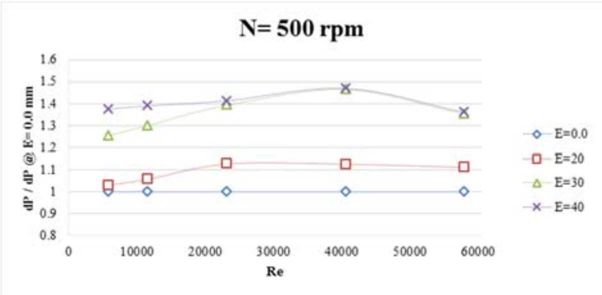

Fig. 11. Eccentricity effect on pressure drop ratio of rotating inner pipe at 500 rpm

Rotation speed effects on Nusselt number ratio at the eccentricity of 40 mm is shown in Figure 12. The present results show that, the maximum heat transfer is achieved at a rotational speed of 500 rpm and an eccentricity of 40 mm.

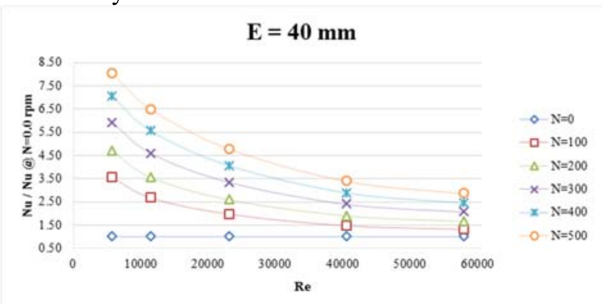

Fig. 12. Rotation speed effect on Nusselt number ratio at eccentricity of 40 mm

4 Conclusion

In the current investigation, a numerical study was carried out to study the performance of double-tube heat exchanger. The heat exchanger performance was investigated with the effect of the inner tube rotation, eccentricity ratio, and Reynolds number. The following conclusions have been obtained:

Rotation of inner pipe of the double pipe heat exchanger enhances the heat transfer rate.

Nusselt number is affected by rotation as it increased by 491 % at low velocity and by 120 % at high velocity compared to the stationary condition. As a result, the outlet temperature increased.

Increasing the eccentricity beside rotation slightly improves the performance of the heat exchanger for both high and low Reynolds number as the Nusselt number increased by 42% at low velocity and by 47% at high velocity.

The effect of rotation on pressure drop obvious in low Reynolds number more than high Reynolds number. Pressure drop raised by 178% at low Reynolds number while it increased by 12% only at high Reynolds number compared to the stationary condition.

Pressure drop is affected by increasing rotation more than the increase in the eccentricity.

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