Magnetic Field Effect on Ferro-Nanofluid Heat Transfer in a Shell and Tube Heat Exchanger with Seven Twisted Oval Tubes

Mansour Talebi*
Reactor and Nuclear Safety Research School, Nuclear Science &
Technology Research Institute, Iran.
E-mail: mansour_talebi@yahoo.com
*Corresponding author

Mehran Tabibian
Department of Mechanical Engineering, Majlesi Branch,
Islamic Azad University, Iran
E-mail: meta_ir@yahoo.com

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Abstract: This article investigates the effect of magnetic field on the performance of a special shell-and-tube heat exchanger using ferro-nanofluid. The heat exchanger comprises seven twisted oval tubes with triangular array mounted on a hexagonal cross section. Water/iron oxide nanofluid with a volume ratio of 4% is used as hot fluid in tubes and water is employed as cooling fluid in the shell. The flow regime is laminar and calculations are performed at different Reynolds numbers and various magnetic fields. The governing equations include continuum, momentum, energy, and magnetic field equations that are solved using a finite volume method. It is demonstrated that the wall temperature of the tubes at the output is lower when the magnetic field is present compared to the case in which the magnetic field is not applied. Applying the magnetic field to the ferro-nanofluid leads to an increase in the Nusselt Number by about two times, leading to an increase in thermal efficiency of the heat exchanger. Also, the effect of the magnetic field was quite different with respect to the geometry and position of the tubes relative to the flow field. The effect of increasing the Nu in the first half of the twisting of the tube is approximately equal to the rate of reduction in the second half of the tube, resulting in a reduction in the impact of the magnetic field intensity.

Keywords: Ferro-Nanofluid, Magnetic Field, Shell and Tube Heat Exchanger, Twisted Oval Tubes

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Biographical notes: Mansour Talebi is Assistant Professor of Mechanical Engineering in Nuclear Science & Technology Research Institute (NSTRI), Iran. He received his PhD in Mechanical Engineering from Isfahan University of Technology, in 2003. **Mehran Tabibian** is a PhD Student in Mechanical Engineering. He received his MSc in Mechanical Engineering from Islamic Azad University, Majlesi branch, in 2018.

Research paper

1 INTRODUCTION

Nowadays, with the development of new technologies in the industry, things like increasing heat transfer rate, reducing heat transfer time, reducing heat exchanger size and finally increasing heat exchanger efficiency are considered. Improvement of the cooling process have been carried out by many researchers using different methods such as the use of fluids with high heat transfer coefficient or nanofluids, change of the geometry of the heat exchangers (HEs), creation of turbulent flow, and the use of magnetic field. Their results have been used in industries. The researchers have employed one or more common methods to increase the heat transfer in HEs.

Tan et al. [1] studied the heat transfer and pressure drop in a twisted oval tube experimentally and numerically and showed that the heat transfer and pressure drop increase in the oval tube. They also examined the effects of geometry on performance of twisted oval tube. Tang et al. [2] compared the turbulent flow characteristics and heat transfer performance of a twisted tri-lobed tube and a twisted oval tube experimentally, showing that the heat transfer performance of a twisted tri-lobed tube is better and its friction coefficient is lower than the twisted oval tube. Duangthongsuk and Wongwises [3] compared the heat transfer of nanofluid with that of water. Aminfar et al. [4] studied the thermal and hydrodynamic behavior of a magnetic nanofluid by considering the electrical conductivity in a vertical rectangular channel and showed that the electrical conductivity has significant effects on the behavior of ferro-nanofluid. They showed that the axial field with negative gradient and the crossing field have similar effects on the Nusselt number (Nu) and friction coefficient, while the axial field with positive gradient decreases the Nu. Shakiba and Gorji [5] investigated the thermal and hydrodynamic behavior of magnetic nanofluids (water/4% iron oxide) in a horizontal double-layer HE under a non-uniform transverse magnetic with different intensities. Sheikholeslami [6] simulated water/copper oxide nanofluid flow in a porous channel numerically. He used the Lattice Boltzmann method and investigated the effect of Reynolds number (Re) and nanofluid volume fraction (φ). Tan et al. [7] numerically simulated the heat transfer and pressure drop of the shell side of a twisted tube HE. They studied the influence of geometrical parameters and showed that Nu and friction coefficient increase by increasing the length of tube and aspect ratio. Mokhtari et al. [8] investigated the nanofluid flow inside a twisted tube numerically and showed the effect of magnetic field on Re. Sheikholeslami et al. [9] simulated the effect of an external magnetic field on water/iron oxide nanofluid flow in an elbow and obtained the flow characteristics. Mousavi et al. [10] investigated the influence of magnetic field on water/iron oxide nanofluid in a dual-tube HE and obtained Nu and temperature variations. Malekan et al. [11] investigated the influence of magnetic field on heat transfer of magnetic Nano fluid in a double pipe HE proposed in a small-scale CAES system. Alsaraf et al. [12] investigated the effect of magnetic field on laminar convective heat transfer. Also, Nazari et al. [13] reviewed the work done on application of Nano fluid in various types of heat pipes. Hatami et al. [14] investigated the effect of magnetic field on nanofluid heat transfer in a tube.

These studies focused mainly on HEs with twisted tubes without magnetic field or considered magnetic field effect on simple geometries. In the present work, the effect of magnetic field and twisted tubes is investigated. The influence of magnetic field and Re on the heat transfer of ferro-nanofluid in a HE with several twisted tubes is investigated. The magnetic field affects the nanoparticles inside the tube and causes the path of particles to change. In this case, the thickness of the thermal boundary layer decreases and the particle collision with the tube wall increases, which is expected to provide a very efficient heat transfer process.

2 PROBLEM STATEMENT

In this paper, the impact of magnetic field on the laminar flow and convection heat transfer of water/Fe_3O_4 nanofluid in a shell-and-tube HE with seven twisted tubes is investigated. The shell has a hexagonal cross-section and seven tubes with triangular array are arranged horizontally in the shell. Figures 1 and 2 show a schematic of the HE tubes. Ferrofluid passes through the tubes as the hot fluid and water flows in the opposite direction through the shell as cold fluid.

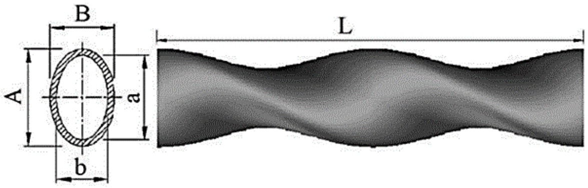


Fig. 1 Schematic of the twisted tube and its cross section.

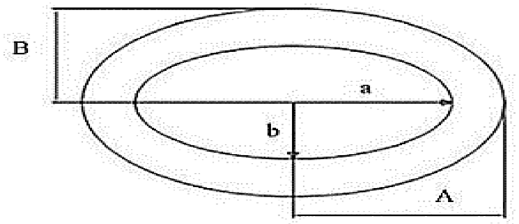


Fig. 2 Oval tube and its parameters.

Figure 3 shows a schematic of the HE and the tubes. The dimensions of the problem are also shown in “Table 1” dimensions specified in “Figs. 1 and 2” (mm). The magnetic field is created by an electrical current passing through a thin wire along the HE axis. The governing equations are continuity, momentum, energy and magnetic field intensity equations that are solved by finite volume method. By determining the flow characteristics, the effect of the magnetic field on the HE performance is obtained. The hot flow enters at 350 °C and water enters at 300 °C. Calculations are performed for Re of 50, 150 and 1620. Non-dimensional magnetic intensities are 5.92×10^5, 2.37×10^6, 5.33×10^6, and 9.47×10^6.

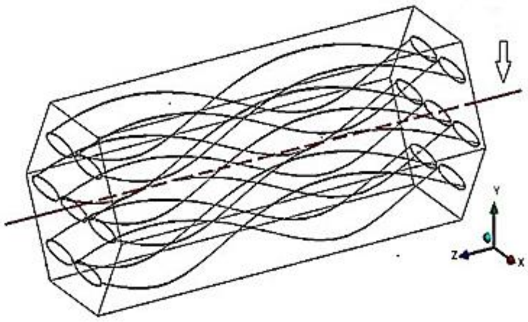


Fig. 3 Schematic of the model.

Table 1 Dimensions specified in “Figs. 1 and 2” (mm)

Shell length	a	b	A	B	Aspect ratio (A/B)
370	5	20	5.86	20.86	4

3 GOVERNING EQUATIONS AND NUMERICAL METHOD

External magnetic field affects physical behavior of ferrofluid. The applied magnetic forces must be considered in the momentum equation. For the calculation of the forces acting on the fluid particles, the ferrohydrodynamic equations are used [11].

When the magnetic field is applied to a nanofluid flow, the following term should be considered in the momentum equation:

$$\mu_0\left(\vec{M}\cdot\nabla\right)\vec{H}+\frac{1}{2}\nabla\times\left(\vec{M}\times\vec{H}\right) \tag{1}$$

Where, H is the magnitude of the external magnetic field and M is calculated by the magnetization law using the Langevin function:

$$M=\frac{6m_p}{\pi d_p^3}\left\{\coth\left(\frac{\mu_0 m_p H}{k_B T}\right)-\frac{k_B T}{\mu_0 m_p H}\right\} \tag{2}$$

Where m_p is the torque of each particle calculated as follows:

$$m_P=\frac{4\times9.27\times10^{-24}\pi d_p^3}{6\times91.25\times10^{-30}} \tag{3}$$

Assuming the magnetic equilibrium of the nanofluid, the following term is considered in the momentum equation:

$$F_{ferromag}=\mu_0 M\nabla\mathrm{H} \tag{4}$$

Therefore, the continuity and momentum equations are:

$$\nabla\cdot\left(\rho_{ff}\overrightarrow{v_{ff}}\right)=0 \tag{5}$$

$$\nabla\cdot\left(\rho_{ff}\overrightarrow{v_{ff}}\overrightarrow{v_{ff}}\right)=-\nabla p+\nabla\left(\mu_{ff}\nabla\overrightarrow{v_{ff}}\right)+\mu_0\left(\vec{M}\cdot\nabla\right)\vec{H} \tag{6}$$

And energy equation:

$$\rho_{ff}C_{p,ff}\left(\frac{\partial T}{\partial t}+\overrightarrow{v_{ff}}\cdot\nabla T\right)=k_{ff}\nabla^2 T \tag{7}$$

In addition, Hx and Hy are the magnetic field components of the wire carrying the electric current with intensity I expressed as follows:

$$H_x(x,y)=\frac{I}{2\pi}\frac{(x-a)}{(y-a)^2+(x-b)^2} \tag{8}$$

$$H_y(x,y)=-\frac{I}{2\pi}\frac{(y-b)}{(y-a)^2+(x-b)^2} \tag{9}$$

Dimensionless magnet number B is calculated using the following equation:

$$M_n=\frac{\mu_0\chi H_r^2 h^2}{\rho_{ff}\alpha_{ff}^2} \tag{10}$$

Where, μ_o is the magnetic permeability of free space, h is cross-section length and α_{ff} is thermal diffusion coefficient and $\chi = 0.348586$ is ferrofluid magnetization coefficient for water/iron oxide nanofluid with $\varphi = 4\%$ and an average diameter of 10 nm. H_r is the characteristic magnetic intensity calculated as follows:

$$H_r=H(a,0)=\frac{I}{2\pi b} \tag{11}$$

Therefore, according to two Eqs.(10) and (11) and the dimensionless magnet numbers assumed in the problem, the current intensity I is calculated. Then, the magnetic field intensity components are calculated by using (8) and (9) and coordinates of each particle.

Because of the small size of the particles, it is assumed that they are easily dispersed in the base fluid and thus behave like a homogeneous fluid. In addition, assuming the slip velocity between the particles, the continuous phase of the base fluid is negligible and the thermal equilibrium condition is established; the nanofluid is considered as a homogeneous single-phase fluid with physical properties based on the concentration of the two components. The thermophysical properties of ferrofluid are calculated using the following equations:

$$\rho_{ff} = \alpha_p \rho_p + (1 - \alpha_p)\rho_f \tag{12}$$

$$\mu_{ff} = \left(1 + \frac{5}{2}\alpha_p\right)\mu_f \tag{13}$$

$$k_{ff} = \left[\frac{k_p + (n-1)k_f - (n-1)\alpha_p(k_f - k_p)}{k_p + (n-1)k_f + \alpha_p(k_f - k_p)}\right] k_f \tag{14}$$

$$C_{ff} = \alpha_p C_{p,p} + (1 - \alpha_p)C_{p,f} \tag{15}$$

“Table 2” Shows the thermo-physical properties of the base fluid and nanoparticles.

Table 2 Thermo-physical properties of the base fluid and nanoparticles

$\rho\left(\frac{kg}{m^3}\right)$	$C_p\left(\frac{J}{kg.K}\right)$	$k\left(\frac{w}{m.K}\right)$	$\mu\left(\frac{kg}{m.s}\right)$	Material
1024	4001.1	0.596	0.00108	Water (*f*)
5200	670	6	-	Fe_3O_4 (*p*)

The assumed HE is such that at the beginning of the inner tube, the nanofluid flow is fully developed and its inlet temperature is known. On the other hand, at the cooling water inlet, the water velocity profile is fully developed and the inlet temperature is given. The inner tube wall is of aluminum and heat transfer is a combination of convection and conduction. The wall is in the vicinity of hot and cold fluids. Thus, the inner tube wall is called the hot wall and the cold fluid side is called the cold wall. The exterior walls of the HE are insulated. The pressure boundary condition is imposed on the HE output for both hot and cold fluids. At the inlet of the hot fluid, there is no velocity in the direction perpendicular to the tube axis and the velocity is only in the direction of the tube.

“Figs. 4 and 5” show an example of the grid used in the tubes and shell. As can be seen, the grid is finer near the walls because of the boundary layer and the need for more precision.

The terms of the magnetic field are added to the solution program by writing the UDF function in C^{++}. By solving the Kelvin equation, the magnetic force is calculated at the nanoparticle coordinates and added to the momentum equation in the x- and y-directions. Finally, the governing equations are solved on the computational domain gridded with SIMPLC algorithm using the finite volume method.

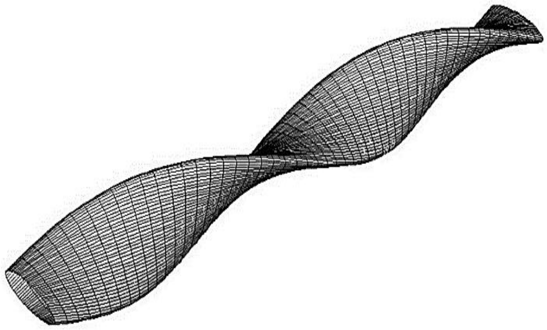


Fig. 4 A view of an elliptical cross section of a twisted tube.

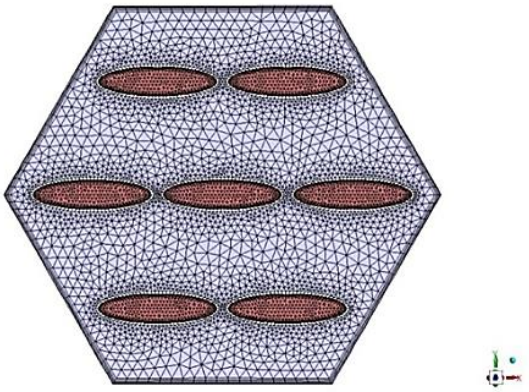


Fig. 5 Example of a cross-sectional grid of the HE with seven twisted oval tubes.

4 RESULTS

To investigate the dependence of the solutions on the grid resolution, numerical solution started with the initial grid and after ensuring convergence in a few steps, the dimensions of the grid were made smaller and the results were again achieved using these new dimensions. “Table 3”. Grid study $\mathrm{Re}_{\mathrm{ff}} = 50, \mathrm{Mn} = 5.92 \times 10^5$ Shows the results of the grid study for the ratio of outer wall temperature to tube inlet temperature. As you can see, the third grid is appropriate.

To verify the results, the flow is first considered for a long horizontal tube under a magnetic field and the water/iron oxide ferro-nanofluid of 4% at Re = 40. The results are compared with those of Aminfar et al. [5]. A comparison of the Nu is shown in “Fig. 6 and Fig. 7”. As it can be seen, there is a good agreement for both cases (with and without the magnetic field).

Table 3 Grid study $Re_{ff} = 50, Mn = 5.92 \times 10^5$

Number of cells	$T_{Wall, out} / T_{in}$
846300	0.00083789
936700	0.000053265
1040395	0.0000016549
1120354	0.0000015675

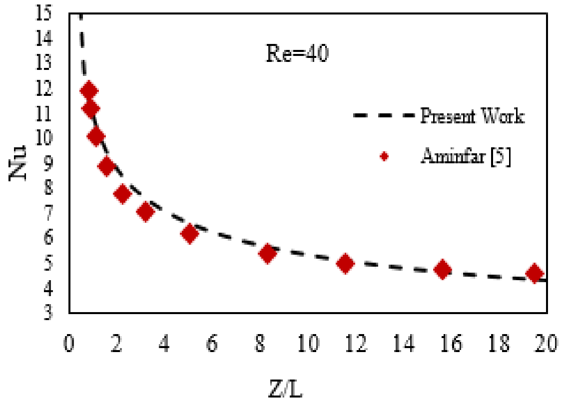


Fig. 6 Comparison of the Nu obtained from the present work and those of Aminfar [5] in the absence of the magnetic field.

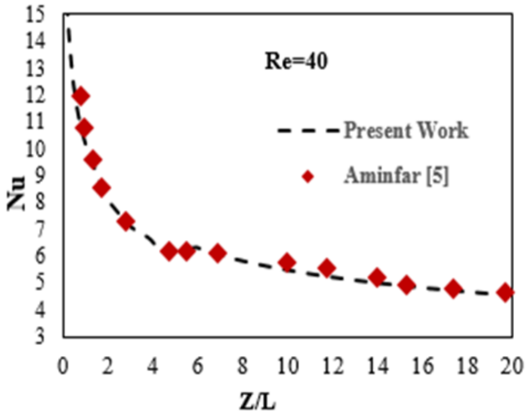


Fig. 7 Comparison of the Nu obtained from the present work and those of Aminfar [5] in the presence of the magnetic field.

As a second verification, the Nu changes versus Re is calculated for a shell-and-tube HE with twisted oval tubes and the results are compared with the experimental data of Tang et al. [2]. As shown in "Fig. 8" there is a good agreement between the numerical and experimental results. Thus, the solution method seems to be appropriate and accurate. Next, the main problem (HE with seven twisted oval tubes) is investigated and flow characteristics are determined. Also, the effect of magnetic field intensity on heat transfer and Nu is calculated. Calculations are performed for different values of Re to determine the effect of Re on the results.

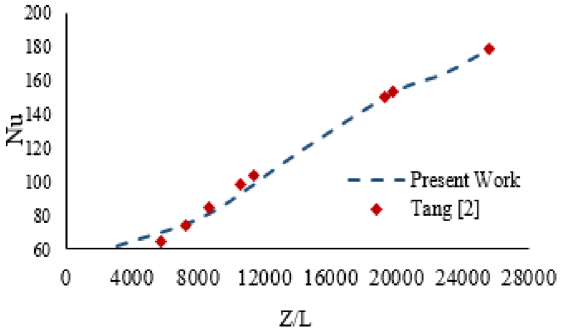
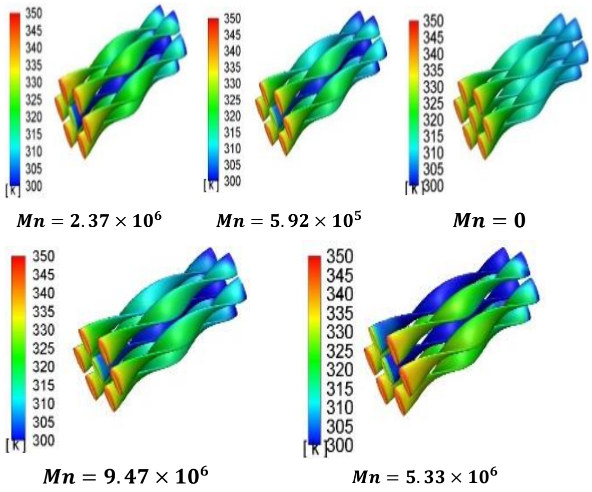


Fig. 8 The Nu versus Re for a twisted tube HE: comparison of present results and those reported by Tang [2].

Figure 9 shows the outer wall temperature contours of the tubes at Re of 150 and different magnetic fields as an example. The figure shows that the temperature of tube wall at the HE output in the presence of the magnetic field is lower than that in the absence of the magnetic field. In other words, by applying the magnetic force, the heat transfer along the tubes increases. Hence, the same performance can be achieved by reducing the size of the HE.



$Mn = 2.37 \times 10^6$ $Mn = 5.92 \times 10^5$ $Mn = 0$

$Mn = 9.47 \times 10^6$ $Mn = 5.33 \times 10^6$

Fig. 9 Wall temperature contour of seven twisted tubes at Re = 150 and different values of magnetic field.

Figure 10 shows the Nu changes along each tube of the HE for Re = 150. As can be seen, for all tubes except the fourth one the Nu increases with the magnetic field. However, due to the geometry of the problem and the ratio of large diameter to small one of oval tubes, the Nu change of each tube is slightly different from that of the other ones. Another reason is the effect of tubes on each other. In the fourth tube, the tube is located in the center of the HE, and the magnetic field is created by a wire passing right through the tube, leading to different variation of Nu.

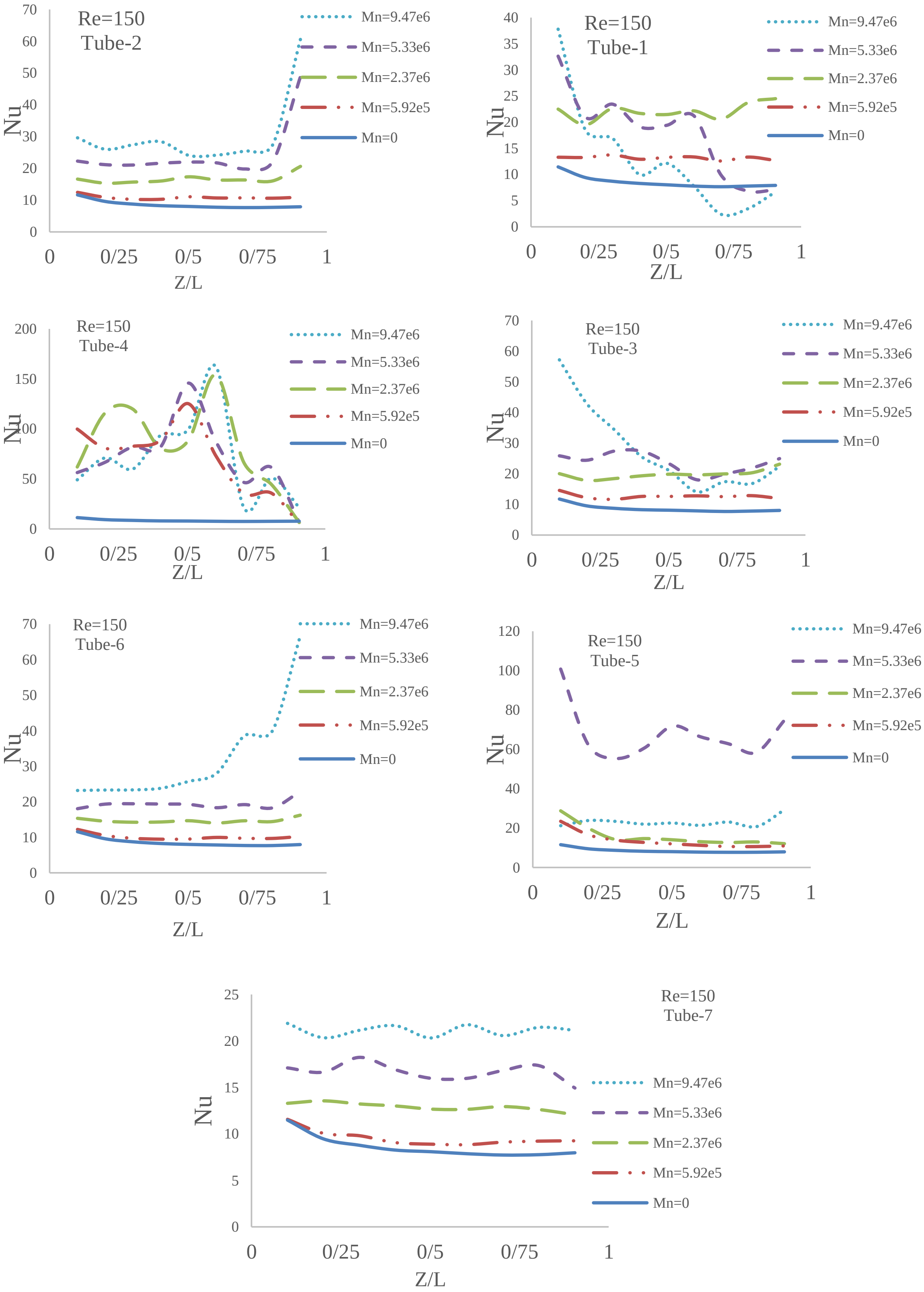
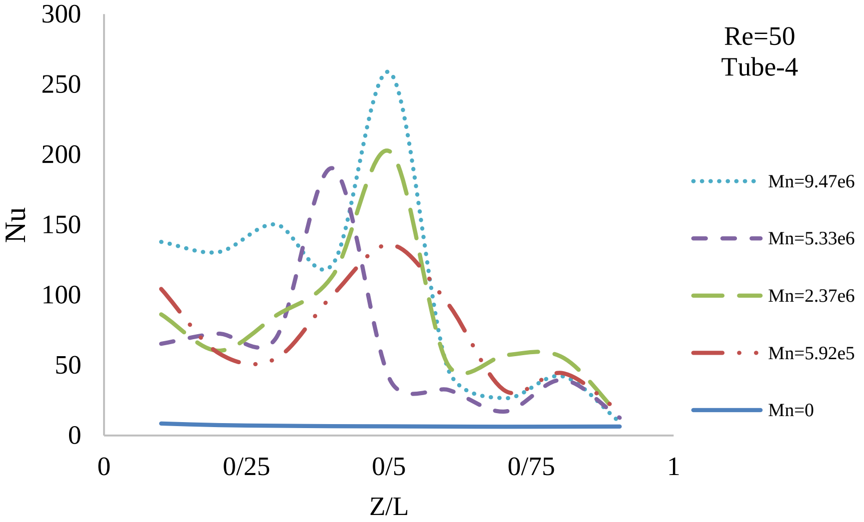
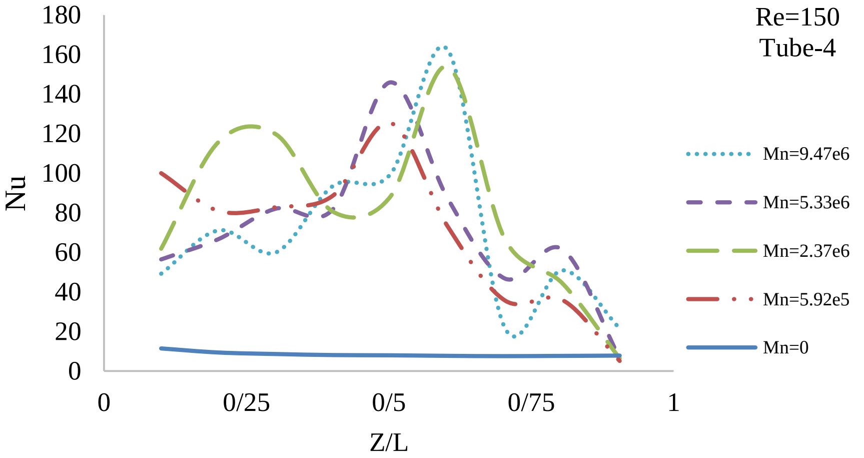


Fig. 10 Nu along the dimensionless length of tube for Re 150.

To better understand the effect of magnetic field and tube position on heat transfer, the results of the four tubes are studied separately. Figure 11 shows the Nu along the dimensionless length for Re of 50, 150, 1620 and different magnetic fields. As can be seen, the direction of twisting of the tube affects the Nu. This is due to the change in the direction of fluid movement during each half pitch of the tube and constant direction of the magnetic field force. In the first half pitch of the tube twisting where the flow direction is in the direction of the magnetic field, the Nu increases. In the next half pitch where the direction of the fluid flow is in the opposite direction to the magnetic field, the Nu decreases. But, in other tubes, due to the asymmetry of the magnetic field and the geometry, the effect of the magnetic field is much greater. However, the Nu is higher than that where there is no magnetic field. Figure 12 shows the variation of the Nu_{av} as a function of Re at different magnetic field intensities. As can be seen, the Nu generally increases by applying the magnetic field. At higher magnitudes of magnetic field, however, the Nu trend changes. For very strong magnetic fields, as the Re increases, the Nu decreases after reaching a maximum. This may be due to the inconsistency of the magnetic field force and the direction of the main flow. Figure 13 illustrates the changes of the Nu_{av} in terms of magnetic field. It is demonstrated that the increase in the Re results in an increase in the Nu. An enhancement of the magnetic field has the same effect. However, strong magnetic fields, not only have no impressive effect on the Nu but also at high Re can decrease it.





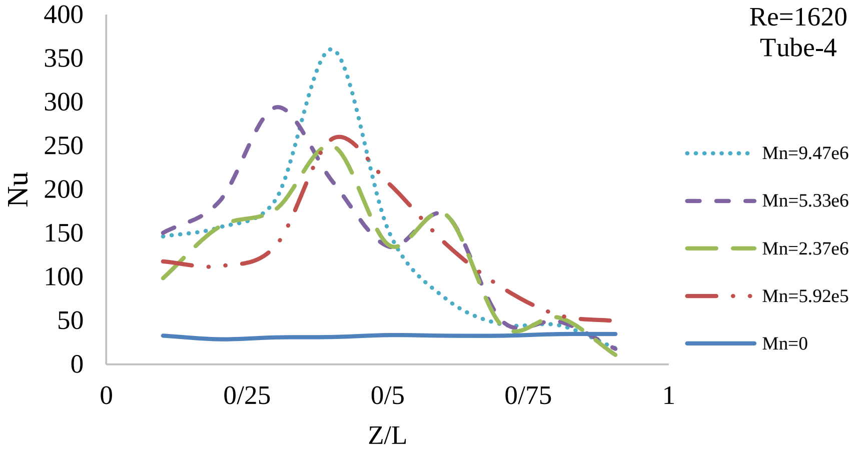


Fig. 11 Local Nu along the fourth tube (middle of the HE).

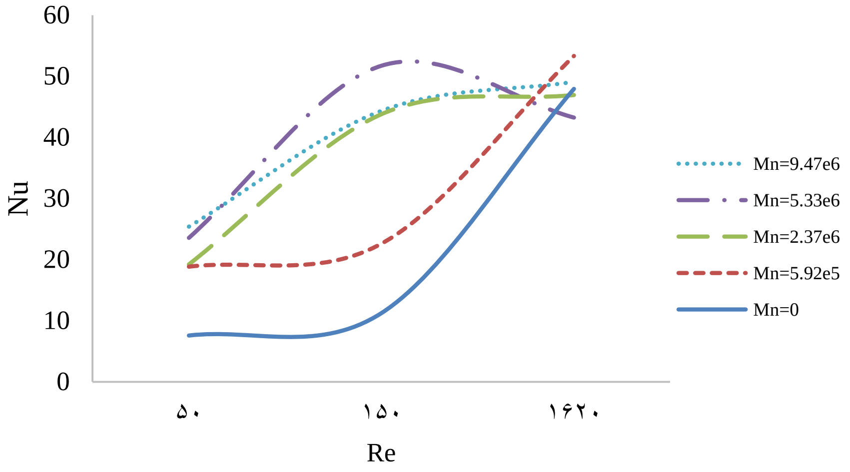


Fig. 12 Variations of the Nu_{av} versus Re for non-dimensional magnetic numbers.

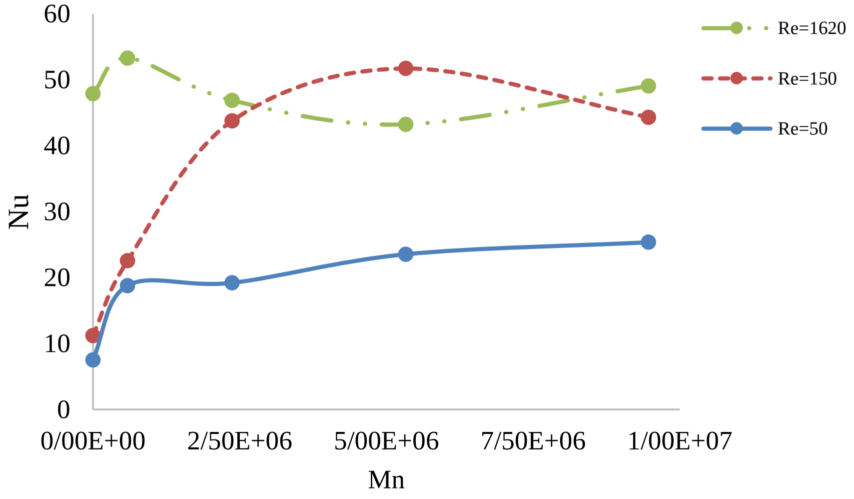


Fig. 13 Variations of the Nu_{av} versus Mn for different values of Re.

5 DISCUSSION AND CONCLUSIONS

In this paper, heat transfer in a specific shell-and-tube HE with seven twisted oval tubes was investigated. The aim of this study was to investigate the effect of magnetic field on heat transfer in the HE using water/iron oxide nanofluid. The governing equations were solved using finite volume method and the flow and heat transfer characteristics were obtained. To validate the results, the flow in a tube in the presence of a magnetic field was first evaluated and compared with the reference results. The flow in a twisted-tube HE was then considered and compared with the experimental results. After the verification, the main problem was simulated in the presence of nanofluids and different magnetic fields to determine the flow characteristics including temperature, heat transfer and Nu. The results showed that the maximum wall temperature occurs in a shorter length of tube inlet by increasing the magnetic field intensity, leading to an increase in the efficiency of the HE. Also, the heat flux of the tube walls and the Nu increase by about two times by increasing the magnetic field intensity. This can be due to the effect of the magnetic field on nanoparticles, which leads them get closer to the surface of the tube. This results in a narrower boundary layer and an increase in the amount of particle contact with the surface of the tube, which ultimately increases the heat transfer. On the other hand, the presence of a cross field along the HE causes turbulence in the fluid stream. The changes of Re were also investigated to investigate the effect of fluid flow and magnetic field on heat transfer. In addition, the effect of the magnetic field was quite different with respect to the geometry and position of the tubes relative to the flow field. If the magnetic field is mounted in the tube, the effect of increasing the Nu in the first half of the twisting of the tube is approximately equal to the rate of reduction in the second half of the tube, resulting in a reduction in the impact of the magnetic field intensity.

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