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Enhanced Heat Transfer in Micromixers with Magnetic Fields: CFD Modeling and Analysis of Ferrofluid Convection

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ABSTRACT

In this paper, the CFD modeling of ferrofluid convection heat transfer in a micromixer with static magnetic field (SMF) and rotating magnetic field (RMF) is investigated. Applying a magnetic field and the existence of magnetic nanoparticles lead to the creation of transverse vortices in the micromixers by the movement of nanoparticles, that improves the heat transfer. There is a cylindrical pit in the microcmixer with the heat source that is applied to its bottom wall. The top wall of the pit is adjacent to a fixed permanent magnet, which creates the SMF. The CFD modeling first is done for the heat transfer process in the micromixer in the absence of the magnetic field. Secondly, simultaneous effect of the SMF and magnetic nanoparticles on the flow pattern and heat transfer rate of ferrofluid is evaluated. Results showed that ferrofluid leads to the improvement of the heat transfer rate compared to pure water. The secondary flows induced by nanoparticles' motion toward SMF decreases the velocity in the area of the application of the magnetic field, so the heat transfer coefficient decreases. But, in the case of RMF, applying the magnetic field causes the nanoparticles to rotate inside the pit, which leads to an increase in the heat transfer coefficient. The CFD results of heat transfer coefficient are compared with experimental results in a reliable reference and acceptable agreement between them is observed.

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1. Introduction

Improving heat transfer using common methods has saved a lot of energy costs and resources and preserved the environment. Magnetic nanoparticles (MNPs) are particles that can be manipulated using magnetic fields and have dimensions of 10 to 100 nm. The suspension with the base of water or organic liquids containing MNPs is called ferrofluid. By applying a magnetic field (MF) to the ferrofluid, the MNPs inside react to it and move under its effect[1–4]. Particles in a ferrofluid mainly consist of nano-sized particles that are suspended by Brownian motion and generally do not settle under normal conditions[5, 6]. In the absence of the magnetic field, the average magnetization of MNPs is almost zero, and with it, they are magnetized and turn into ferromagnetic particles. If the size of MNPs is 100 nm to 1 µm, the formed suspension is called a magnetorheological (MR) Fluid. In the MR fluid, the particles are too heavy to stay in suspension due to Brownian motion, so they settle over time[7]. Its unique properties make it more effective than other nanostructures. The unique properties of magnetic nanoparticles with dimensions below 20 nm include superparamagnetism and magnetic super-saturation, which originate from their inherent magnetic properties. The simultaneous possession of liquid and superparamagnetic properties is one of the most important features that leads to the magnetic control of ferrofluids. Among the nanomaterials used to make ferrofluids, magnetic nanomaterials such as Fe_3O_4, γ-Fe_2O_3, Co, Fe, or FeC, which are stably dispersed in a carrier liquid, nowadays, Fe_3O_4 magnetic nanoparticles have been receiving more attention due to their many applications, easy synthesis and biological versatility[8, 9]. The movement of nanoparticles with magnetic field in the relevant device in the direction of the applied MF causes transverse flows or secondary flows, which improve the mixing, mass and heat transfer[10–13]. The behavior of MNPs in the base fluid that is subjected to the magnetic field depends on the characteristics of the applied MF and its nature [14, 15]. Magnetic nanoparticles have recently been widely used to improve heat transfer in microtubes and micromixers due to the induction of turbulence and irregular motions in the fluid and enhanced mixing [16]. In continuous mixing process, the movement of MNPs is subjected to the magnetic force in addition to hydrodynamic forces (the fluid flow). The creation of transverse vortices in the mixing channel of micromixers by the movement of nanoparticles under the magnetic field is a method that increases the interface between two fluids. The main plan in this method is to create a convection transfer mechanism in addition to the molecular transfer through stretching, twisting and breaking of fluid elements in the laminar flow [16]. With the progress of science and technology, more attention has been paid to the manufacture of tools and instruments in micro and nano dimensions due to the reduction of energy loss and increase in efficiency. With the reduction in dimensions, the heat dissipation is still a fundamental issue, and it is obvious that radiators and air-conditioning exchangers with macro dimensions are not efficient in micro installations. The reason behind is that the heat flux in this device is on the scale of MW/m^2, which is outside the efficiency range of the macro exchangers. As a result, the design, analysis and use of micro-exchangers is one of the attractive research topics of the day. Considering the difficulty and high cost of experimental tests in micro dimensions, the numerical analysis can be a useful method in this field. Bezaatpour et al. [17] studied the

effects of the external magnetic field and fins on the convection heat transfer in a solar thermal system. Heat transfer improves by increasing the volume fraction, fin porosity, and magnetic field intensity and decreases by increasing the Reynolds number. Nessab et al. [18] studied a numerical solution of the convection heat transfer on top and bottom walls which are exposed to a constant heat flux insulated at the thermal input. For the ferrofluid flow, the hydrodynamic (FHD) and thermophoresis effects as well as Brownian motion are considered. Ghorbani et al. [19] studied the effect of the external magnetic field on the thermal heat transfer of a flow of fluoride by a numerical model. Seo et al. [20] performed the CFD modeling inside a microchannel under the magnetic field with the COMSOL simulation software. Effect of the magnetic field direction on the flow and thermal behavior was numerically investigated. According to the reviewed studies, it can be said that the purposeful movement of magnetic nanoparticles in single-phase and two-phase systems under magnetic fields has the ability to improve the heat and mass transfer. The size of particles, the geometry of the mixing device, and the nature of the magnetic field are among the parameters that affect the heat transfer rate. Most of the researches have focused on the use of microchannels and tools in micro dimensions and applying magnetic fields on them in order to motivate magnetic particles. The Reynolds number of this equipment is very low, because this equipment has a small size. Therefore, in a process such as mixing, the flow is never turbulent and the mixing efficiency is very poor. Indeed, in laminar regime the mixing is only affected by the molecular diffusion, and therefore, a long path and high time are needed to reach a suitable mixing degree. However, most of the above studies were performed experimentally, while it can be done by the CFD modeling of the ferrofluid flow under magnetic fields to provide an overview of the hydrodynamics of the fluid flow under the magnetic field. Before applying magnetic nanoparticles in micromixers, designers can estimate the time and dimensions required for mixing and the mass transfer with the CFD modeling. The novelty of this research is the CFD modeling and comparing the effect of the static magnetic field (SMF) and rotating magnetic fields (RMF) on the improvement of the heat transfer inside micromixers. The heat transfer coefficient in various flow rates and Reynolds numbers (Re) is considered.

2. Simulation

2.1. Geometry

In this research, the CFD modeling of a micromixer with a cylindrical pit, while a constant heat flux ($62\frac{kW}{m^2}$) is applied to its bottom surface, is performed. In order to confirm modeling results, the studied geometry (pitted micromixer) was selected from the research of Karami et al. [7]. Figure 1 shows the real photo of the experimental setup[7]. The first step in performing the simulation is the modeling of the micromixer geometry and its grid. The studied micromixer consists of three layers, which are designed and meshed in the Gambit 2.4. software. The micromixer includes an inlet with the width and height of 0.8 mm and a length of 35 mm and a central cylinder with a diameter of 50 mm and a height of 0.8 mm. In the bottom part of the micromixer, there is a rectangular plate with a thickness of 0.8 mm made of steel.

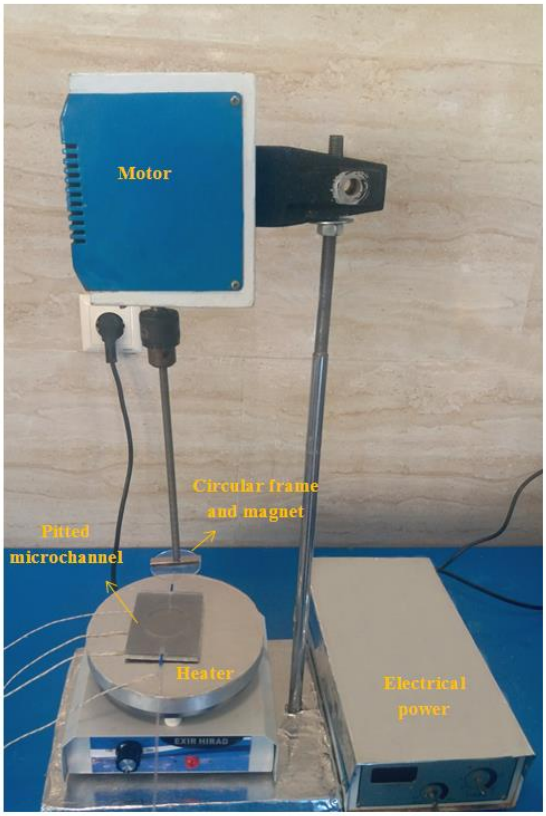


Figure 1. Actual photo of the micromixer and experimental system [7].

2.2. Gridding

Triangular meshes with a size of 0.001 cm are used for meshing the volume of the micromixer. For more accuracy, finer meshes were used on the inlet and outlet faces. The volume of the computing area is gridded with hexahedron meshes and the size is 0.1 cm, and finally the volume of the meshes is 105760.

2.3. Boundary conditions

For this model, the boundary conditions are the velocity inlet for the micromixer inlet, the outlet flow for the outlet of the micromixer, the wall boundary condition for the side and bottom surfaces of the micromixer, which are presented in Table 1.

Table 1
Boundary conditions

Boundary zone	Type
Fluid inlet	Velocity inlet
Fluid outlet	Outflow
Bottom wall	Wall
Top wall	Wall

2.4. Numerical calculations

After preparing the 3D geometry of the micromixer in the Gambit software, the aforementioned geometry was read by the Fluent 6.3. software. Calculations in the Fluent software are done in two steps. In the first step, the heat transfer of the ferrofluid without magnetic fields is considered. In the second step, the flow pattern and heat transfer rate of the ferrofluid under the effect of magnetic fields are investigated. These calculations were done at a constant pressure (*1 atmosphere*). Table 2 shows the characteristics of the ferrofluid[7].

Table 2
Specifications of the ferrofluid.

Parameter	Definition
Density of ferrofluid-inlet	1050 kg/m^3
Viscosity of ferrofluid-inlet	0.00113 kg/m^3
Magnetic permeability of ferrofluid-inlet	0.11H/ m

3. Governing equations

The continuity equation for the one-phase flow is [20]:

$$\frac{\sigma\rho}{\sigma t} + \nabla.(\rho v) = 0 \qquad (1)$$

Where ρ is density, ν is the fluid velocity, and t is time.

The momentum equation is:

$$\rho\left(\frac{\sigma v}{\sigma t} + v \times \nabla v\right) = -\nabla p + \mu\nabla^2 v \qquad (2)$$

Where P is the static pressure, ν is the fluid velocity and μ is viscosity. In case of applying magnetic fields, the magnetic field should be added to Eq. (2) so the new version of this equation is as follows [4]:

$$\rho\left(\frac{\sigma v}{\sigma t}+v+\nabla v\right)=-\nabla p+\mu\nabla^2 v+\mu_0(M\nabla)H \quad (3)$$

here M is the magnetization value, μ_0 is the vacuum magnetic permeability, and H is the magnetic field strength. If M is aligned with the applied magnetic field (H), or H is strong enough, the magnetization equation is written as[4]:

$$M=\chi H \quad (4)$$

Maxwell's law was used to define the current density (J (A/m^2)) and H (A/m) as follows[4]:

$$\nabla\times H=J \quad (5)$$

Therefore, Gauss' law to define B (V/m^2) is written as follows:

$$\nabla\times B=0 \quad (6)$$

The structural equation to explain the relationship between B and H is as follows[4]:

$$B=\mu_0(\mathrm{H}+\mathrm{M})=\mu_0(1+\chi)\mathrm{H} \quad (7)$$

Where χ is the permeability of the operating fluid.

4. Solution strategy

Considering that the studied system is a micromixer, the calculations were performed based on the laminar flow regime. The field strength is equal to 0.12, 0.35 and 1.2 T. The designed tube has an inlet where the ferrofluid with a density of 1050 kg/m^3 and a viscosity of 0.113 kg/m.s enters it.

5. Results and discussion

5.1. Hydrodynamic (HD) and magnetohydrodynamic (MHD) flow modeling in a pitted micromixer

Modeling was done in two steps without using magnetic fields and nanoparticles and at the presence of magnetic fields and nanoparticles. The obtained results are drawn graphically and analyzed further. The HD flow model and MHD flow model were investigated in a pitted micromixer. Figure 2 shows the contour of the velocity for the ferrofluid and water in the micromixer (HD flow) by applying SMF. The velocity of the ferrofluid at the inlet was set to 0.0026042 m/s (Re=2) and the initial water temperature was set to 20°C. Figure 3 shows the velocity contour of water and the ferrofluid in the micromixer with SMF applied on top of the cylindrical pit (MHD flow). Also, the inlet velocity was 0.0026 m/s (*Re*=2). By the comparison of Figures 2 and 3, it can be seen that by using magnetic fields, the velocity has decreased due to the motion of nanoparticles towards the magnetic field with the maximum flux, so; the form of the flow is changed and also the flow pattern varied. The reason behind is that the ferrofluid is under two magnetic and hydrodynamic forces. In this study, SMF is placed at the top of the pit and perpendicular to the ferrofluid inlet. So, the Kelvin force (the magnetic volumetric force) is applied to the fluid. Figure 4 shows the velocity contour of the ferrofluid flow under the effect of rotating magnetic fields in a horizontal slice of the micromixer (y=0). As it is known, by applying a rotating magnetic field on the upper part of the pit, due to the rotation of the nanoparticles inside the ferrofluid, the base fluid also rotates, so more values of the fluid velocity are observed in this area compared to the same in the SMF field. Figure 5 shows the total pressure distribution for HD and MHD flows in the micromixer. In the HD flow, the pressure is equal to 1013500 *Pa* at the beginning, which is decreasing along the length of the inlet channel of the micromixer, increases again in the pit due to its width, and then decreases again when it reaches the outlet channel. The

pressure changes for the HD flow has a decreasing trend, while in the MHD flow, the pressure suddenly decreases in the region of the pit that is under the effect of the magnetic field. Indeed, in the MHD flow, the pressure distribution decreases along the walls on the place of applying the magnetic field. The high pressure drop is related to the areas with the maximum magnetic flux density. Figure 6 shows the velocity magnitude distribution on the center line of the micromixer. X is the distance from the intersection of two inlet channels, L is the length of the micromixer. In the case of SMF, the average velocity value for the HD model is approximately 0.0029 m/s, while in the MHD model, the velocity decreases in the region of applying the magnetic field. The SMF applied on the upper wall of the micromixer causes a decrease in the velocity of flow in the pit, while for RMF, the velocity magnitude in this region increased.

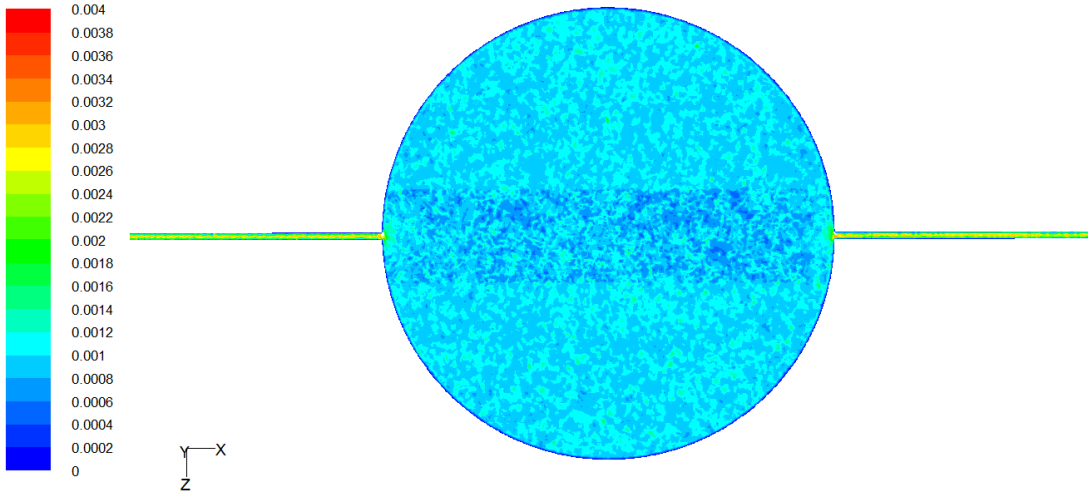


Figure 2. Velocity contour for the HD flow in a horizontal cross-section and applying SMF (y=0).

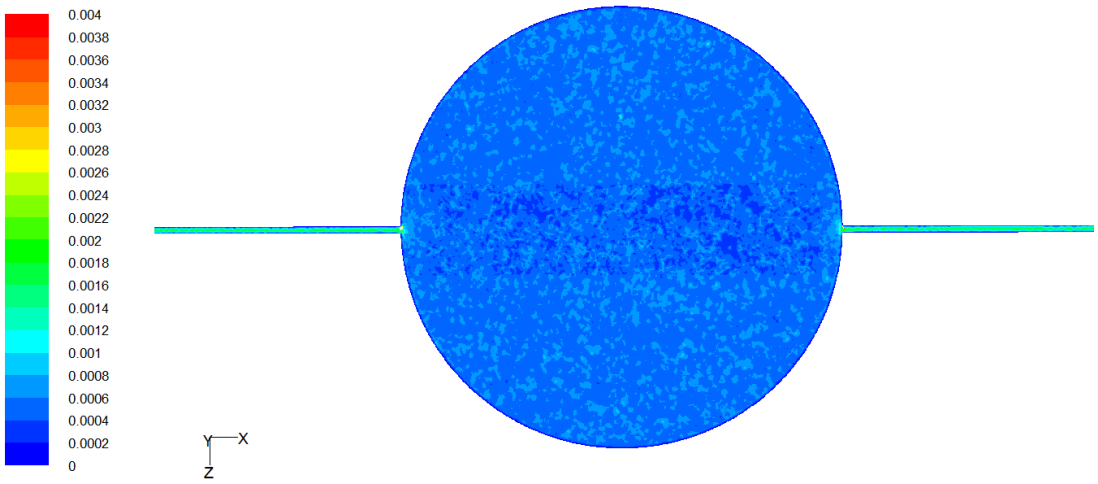


Figure 3. Velocity contour for the MHD flow in a horizontal section and applying SMF (y=0).

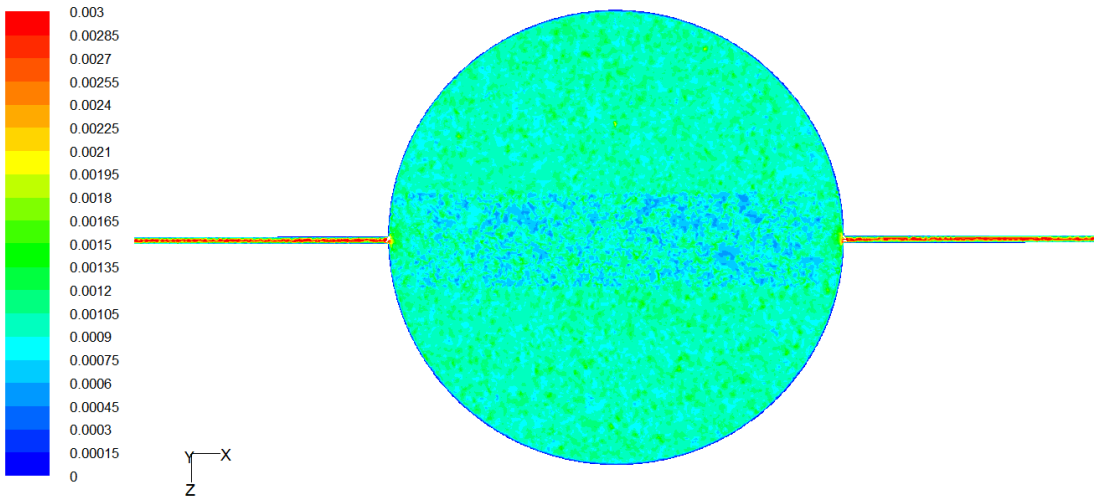
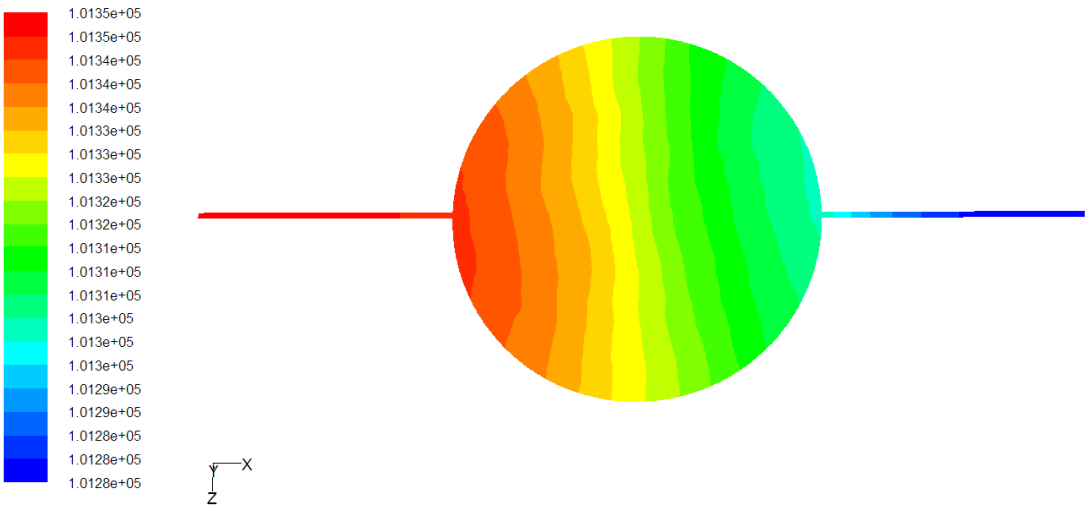
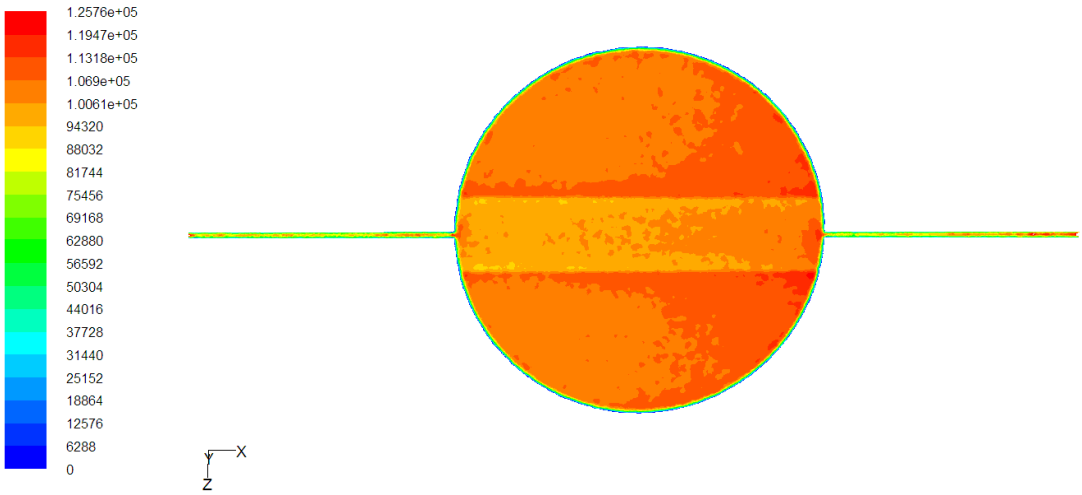


Figure 4. Velocity contour for the MHD flow in a horizontal section and applying RMF (y=0).



(a)



(b)

Figure 5. Static pressure contour in a horizontal cross-section and applying SMF (y=0) with the ferrofluid flow velocity of 0.0029 m/s. (a) the HD model, (b) the MHD model.

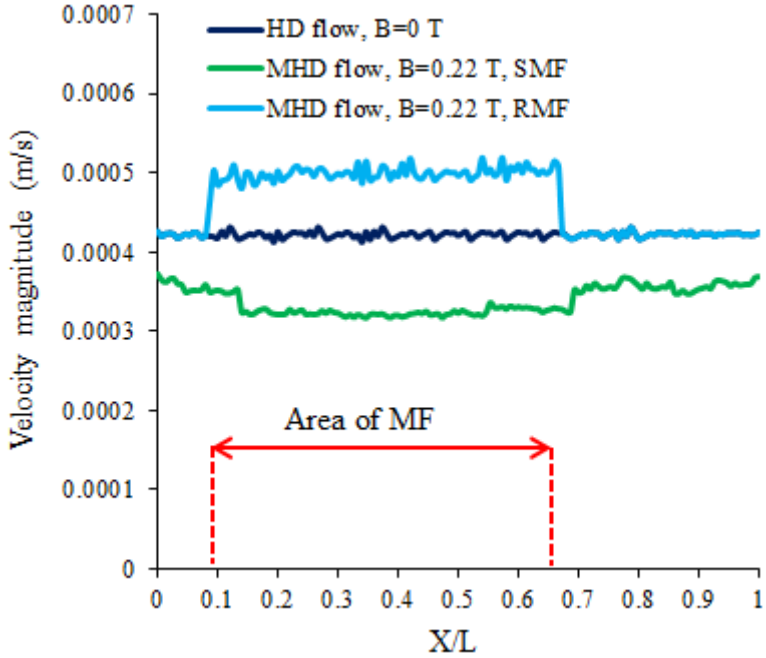
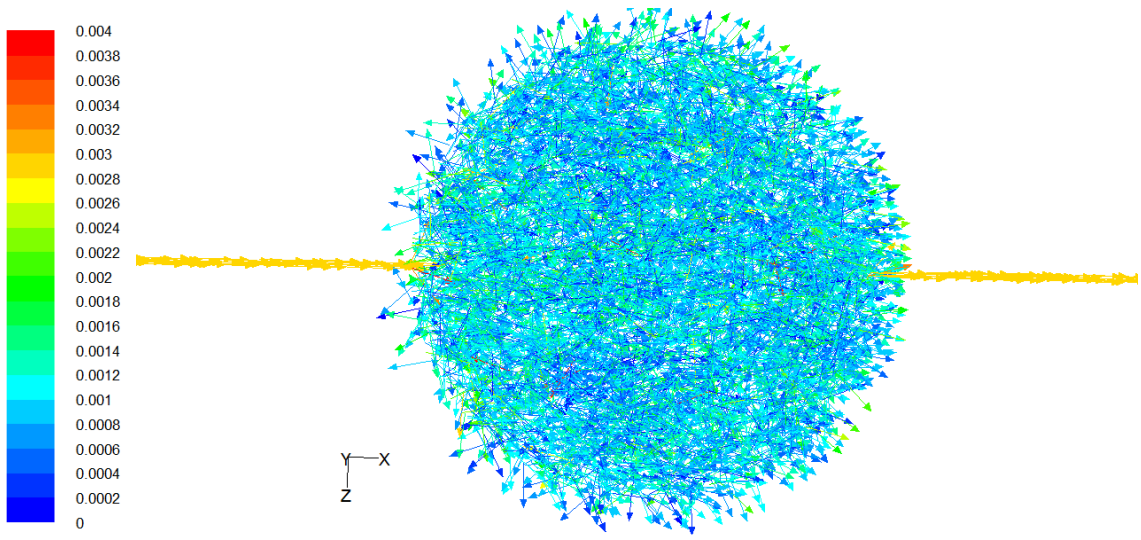
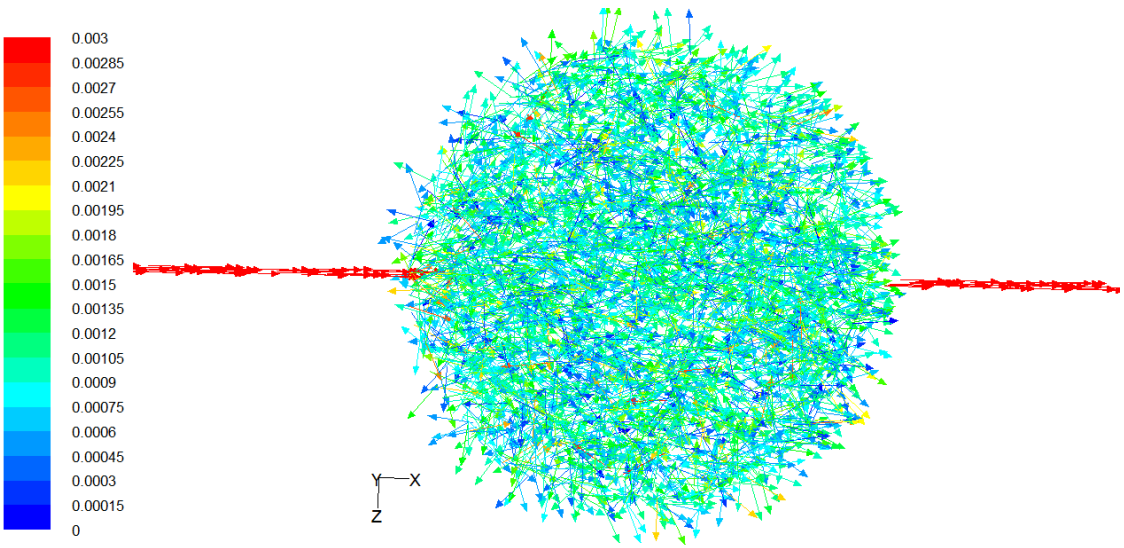


Figure 6. Velocity in the flow direction in the central line of the micromixer and the inlet flow velocity of 0.0029 m/s and B=0.22 T.

The movement perpendicular to the flow of nanoparticles leads to the formation of a vortex, creating chaos in the flow and reducing the velocity. These results agree to the effect of SMF on the MHD flows that arereported in the references[4]. Figure 7 shows the velocity vectors in the pitted micromixer. By applying SMF on the pit, it can be seen that the velocity values are lower than those of RMF and the flow shape is more irregular.



(a)



(b)

Figure 7. Velocity vectors (m/s) in the horizontal slice (y=0), (a) SMF, (b) RMF.

5.2. CFD modeling results based on outlet temperature and Nusselt number

In the study done by Karami et al. [7], the outlet flow temperature was measured at four different flow rates (Re=2, 4, 6, and 8). The experiment was done for the ferrofluid without magnetic fields and also the ferrofluid by using the SMF and RMF, and results of the outlet temperature of the fluid bulk (T_b) are shown in Figure 8. The average value of the heat transfer coefficient (h_{ave}) and Nusselt number can be calculated using following equations:

$$h(x) = \frac{q_w}{T_w(x) - T_b(x)} \tag{8}$$

Where q_w is the heat flux on the bottom wall of the micromixer, and T_b is the fluid bulk temperature and T_w is the wall temperature. Figure 8 shows the CFD of h_{ave} by investigating the effect of SMF and RMF. Therefore, the CFD modeling was done for four the Reynolds numbers of 2, 4, 6 and 8. To confirm the modeling results, the CFD data are compared with the experimental data in Karami et al. [7]. In this figure, it can be seen that h_{ave} has the highest value for the ferrofluid flow with RMF while SMF has the lower values of h_{ave}. This means that applying SMF on the pitted micromixer does not improve the heat transfer, but when RMF is applied, the values of h_{ave} is higher than its values for SMF and without MF. The applied RMF magnetic field causes the secondary flow that increases the velocity and the mixing inside the pit, so, the heat transfer rate also increases.

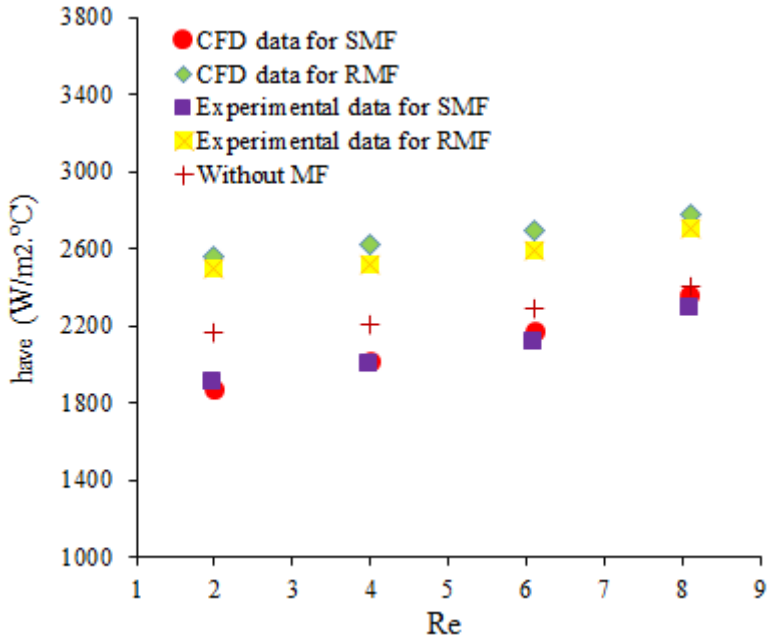
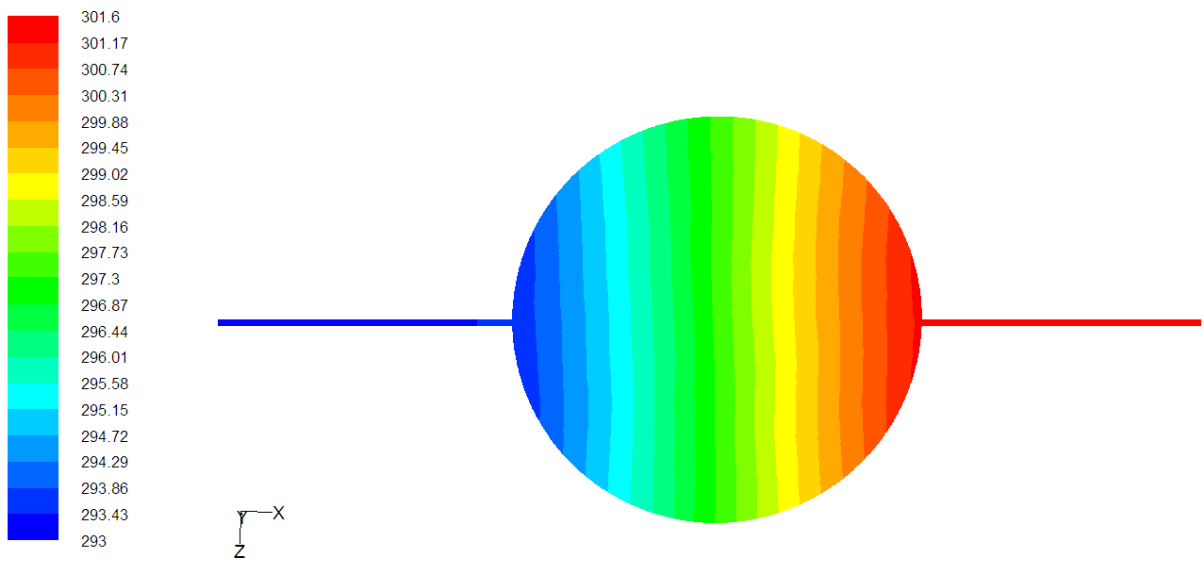
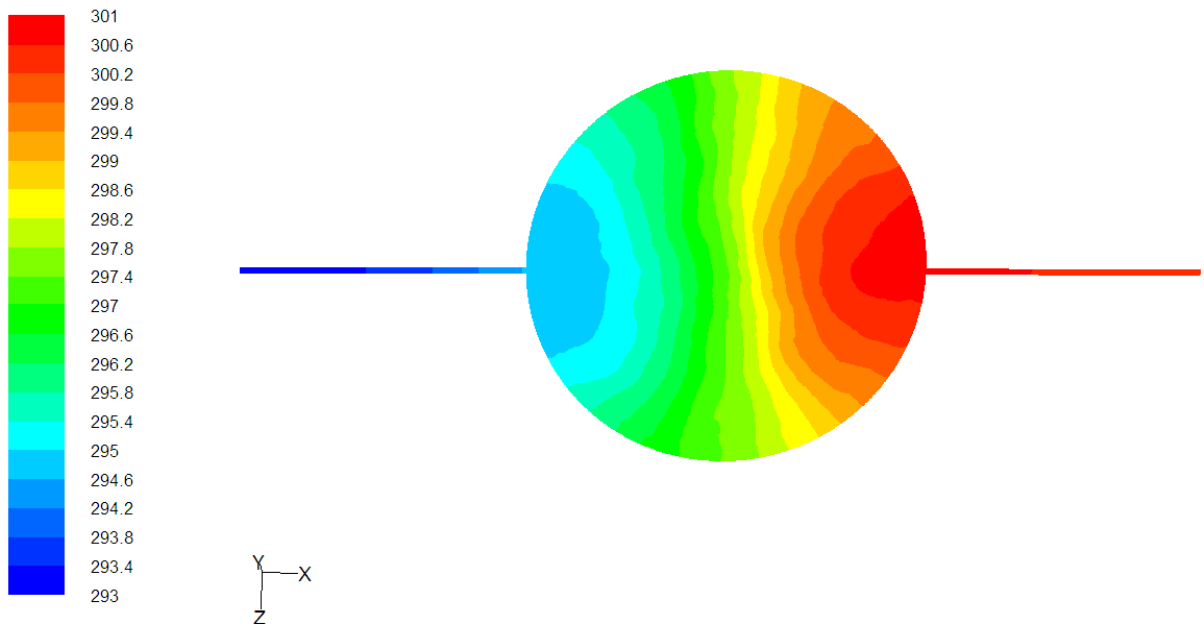


Figure 8. Results of the average heat transfer coefficient (h_{ave}) by applying SMF and RMF, B=0.125 T.

As Figure 9 shows, the temperature of the ferrofluid exiting from the micromixer seen in the CFD modeling for the HD flow is lower than for the MHD under SMF.



(a)



(b)

Figure 9. Ferrofluid outlet temperature contour for the ferrofluid (a) HD and, (b) the MHD flow with SMF.

In the case of SMF, the transverse movement of nanoparticles and its base fluid leads to the creation of a vortex and a decrease in the velocity, so the heat transfer coefficient decreases. These results agree with the MHD flow modeling results reported by Karami et al. [7].

6. Conclusion

The CFD modeling of the convection heat transfer for the ferrofluid flow inside a pitted micromixer with the static magnetic field (SMF) and the rotating magnetic field (RMF) was investigated. Results depicted that applying the magnetic field on magnetic nanoparticles inside the flow leads to inducing transverse vortices in the micromixers. Indeed, the motion of nanoparticles toward the rotating magnetic field (RMF) improves the heat transfer, but it is the opposite for the static magnetic field (SMF). The pressure distribution in the HD flow decreases linearly for the micromixer, while in the MHD model, the pressure decreases suddenly in the region of the magnetic field. The average value of the heat transfer coefficient (h_{ave}) in different flow rates and Reynolds numbers is considered. Results showed that the ferrofluid leads to the improvement of the heat transfer rate compared to pure water. The secondary flows induced by the nanoparticles' motion toward SMF decreases the velocity in the area of the magnetic field, so the heat transfer coefficient decreases. But, in the case of RMF, applying the magnetic field causes the nanoparticles to rotate inside the pit, which leads to an increase in the heat transfer coefficient. CFD results were compared with experimental results in a reliable reference and acceptable agreement between them was observed.

Nomenclature

B magnetic field (T)

H magnetic field strength (A/m)

h_{ave} average heat transfer coefficient ($W/°C.m^2$)

J	Electric current density (A/m^2)
M	Magnetization (A/m)
P	Pressure (Pa)
Re	Reynolds Number
Tb	Outlet Temperature (℃)
χ	Permeability of the operating fluid

Greek letters

ρ	Density ($kg/m^{3)}$
ν	velocity (s/m)
μ	Viscosity (Kg/m.s)
μ_0	Vacuum magnetic ($J/A^2.m$)

Superscripts and subscripts

HD	Hydrodynamic
MHD	Magnetohydrodynamic
MF	Magnetic field
SMF	Constant magnetic field
RMF	Rotating magnetic field

Reference

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