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Numerical analysis of magnetic field effects on hydro-thermal behavior of a magnetic nanofluid in a double pipe heat exchanger

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ABSTRACT

This study attempts to numerically investigate the hydro-thermal characteristics of a ferrofluid (water and 4 vol% Fe_3O_4) in a counter-current horizontal double pipe heat exchanger, which is exposed to a non-uniform transverse magnetic field with different intensities. The magnetic field is generated by an electric current going through a wire located parallel to the inner tube and between two pipes. The single phase model and the control volume technique have been used to study the flow. The effects of magnetic field have been added to momentum equation by applying C++ codes in Ansys Fluent 14. The results show that applying this kind of magnetic field causes kelvin force to be produced perpendicular to the ferrofluid flow, changing axial velocity profile and creating a pair of vortices which leads to an increase in Nusselt number, friction factor and pressure drop. Comparing the enhancement percentage of Nusselt number, friction factor and pressure drop demonstrates that the optimum value of magnetic number for $Re_{ff}=50$ is between $Mn=1.33\times10^6$ and $Mn=2.37\times10^6$. So applying non-uniform transverse magnetic field can control the flow of ferrofluid and improve heat transfer process of double pipe heat exchanger.

1. Introduction

With the growth and development of modern technologies, special attention is paid to heat transfer; decreasing the time of heat transfer, minimizing the size of heat exchangers, and finally maximizing the efficiency of thermal equipment. It is important to improve cooling methods by fluids which is one of the major challenges in reducing energy consumption of many industries such as electronics, transportation, power production, and machining [1]. Thermal conductivity is one of the effective characteristics of fluids in heat transfer processes; by increasing this characteristic, rate of heat transfer can be improved. Since metals in comparison to conventional fluids such as water and ethylene glycol have higher thermal conductivities, combining these two materials in order that a thermal transfer environment with metal thermal conductivity is created which acts like a fluid would be of great use.

At first, particles bigger than nanometer were used which caused problems such as blockage and abrasion of fluid pipes, instability, quick deposition of the base fluid, and an increase in pressure drop. Contrary to those particles, nanopowders have more surface area, less momentum and more mobility, so they replaced the bigger particles.

Choi is known as an innovator in using dispersed nanoparticles in base fluids [2]. Wangwises et al. have investigated heat transfer of TiO_2 nanoparticles in water [3]. They concluded that using nanofluids instead of water would increase heat transfer in a double pipe heat exchanger. In an experiment, Kannadasan et al. [4] examined heat transfer and pressure drop of water–CuO nanofluid in a spiral heat exchanger. They concluded that by using nanofluids, the Nusselt number in volume concentrations of 0.1% and 0.2% increases by 37% and 49% accordingly. Zamzamian et al. [5] in an experimental work used Alumina–Ethylene glycol and CuO–Ethylene glycol to examine forced convective heat transfer in double pipe and plate heat exchangers. Huminic et al. [6] in a numeric work examined nanofluid heat transfer in a helical double pipe heat exchanger in laminar flow. They concluded that by using nanofluids such as TiO_2 and Cuo dispersed homogeneously in water as the base fluid, maximum increase in convective heat transfer coefficient can be reached. Also, they found out by adding to the volume fraction of nanoparticles, heat transfer increases.

In recent years, scientists and engineers have been paying attention to the ability of controlling fluids hydrodynamically or thermally. One suitable way is to use magnetic fluids and magnetic fields. Magnetic nanofluids or ferrofluids are, in fact, a special type of nanofluids with magnetic nanoparticles such as $CoFe_2O_4$, γ-Fe_2O_3, Fe_3O_4, Fe, CO and FeC that mean diameter of them are

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Nomenclature

(a,b)	center of magnetic wire (m)
$\vec{H}$	magnetic field vector (A/m)
c_f	friction factor $C_f = \frac{\tau_w}{1/2\rho_{ff}V_{0,hot}^2}$
c_p	specific heat (J/kg K)
d_p	magnetic particle diameter (m)
H_y	magnetic field intensity component in y direction (A/m)
H_z	magnetic field intensity component in z direction (A/m)
I	electric intensity (A)
k	thermal conductivity (W/m K)
k_B	Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)
L	Langevin function
M	magnetization (A/m)
Mn	magnetic number $\mathrm{Mn} = \frac{\mu_0 \chi H_r^2 h^2}{\rho_{ff}\alpha_{ff}^2}$
m_p	particle magnetic moment
Nu	Nusselt number $\mathrm{Nu} = \frac{q_w(2r_i)}{k_{ff}(T_w - T_b)}$
P	pressure (Pa)
p	perimeter (m)
Re	Reynolds number
r_i	inner tube radius (=0.0125 m)
T	temperature (K)
$\mathrm{T}_{0,\mathrm{hot}}$	hot fluid inlet temperature (=313.15 K)
$\mathrm{T}_{0,\mathrm{cold}}$	cold fluid inlet temperature (=293.15 K)
$V_{0,\ \mathrm{cold}}$	inlet velocity of cold fluid (m/s)
$V_{0,\ \mathrm{hot}}$	inlet velocity of hot fluid (m/s)
x	axis in the Cartesian coordinates
y	axis in the Cartesian coordinates
z	axis in the Cartesian coordinates

Greek letters

α_{ff}	thermal diffusivity($=1.5994815 \times 10^{-7}$ m^2/s)
α_p	particle volume fraction
ζ	Langevin parameter
μ	dynamic viscosity (kg/m s)
μ_0	magnetic permeability in vacuum($=4\pi \times 10^{-7}$ T m/A)
μ_B	Bohr magneton ($=9.27 \times 10^{-24}$ A m^2)
ρ	density (kg/m^3)
χ	magnetic susceptibility

Subscripts

0	pertaining to inlet conditions
f	pertaining to base fluid
ff	pertaining to ferrofluid
p	pertaining to magnetic particles

around 3–15 nm; these particles are dispersed constantly in a base fluid like water, petroleum, industrial oil, ethylene glycol compounds, etc. The ability to control fluid flow, heat transfer and particle movement by using magnetic fields, in addition to increasing heat transfer, are particular characteristics of magnetic nanofluids. These characteristics have encouraged different engineering branches such as heat transfer, electronic, medical, etc. to use magnetic nanofluids when choosing the desired fluid. Ferrofluids have applications in heat transfer, electronic devices, friction decrease, military usages, analysis equipment, aerospace, medicine, optics, arts, and so on [7–10].

In spite of wide research in nanofluid heat transfer, few studies have been conducted on examining flow and heat transfer of magnetic nanofluids. Ghofrani et al. [11] studied the forced convective heat transfer of a ferrofluid in a pipe exposed to a variable magnetic field, and realized using a magnetic field increased the rate of convective heat transfer. During an experiment, Li et al. [12] studied the characteristics of convective heat transfer in magnetic nanofluids exposed to an external magnetic field. The results showed that a magnetic field had a significant effect on magnetic nanofluid convective heat transfer, and heat transfer processes can be controlled by using an external magnetic field.

In an empirical and numeric experiment, Zablotsky et al. [13] examined thermo-magnetic convective heat transfer of a ferrofluid with temperature graded properties before non-uniform magnetic fields. The experiment was done on a rectangular cell with permanent magnets installed on its walls. When the cell is heated from below before a magnetic field, heat transfer rate increases significantly. These findings are consistent with numerical results to a great extent.

In an experiment, Lajvardi et al. [14] investigated the forced convective heat transfer of water–iron oxide magnetic nanofluid flowing through a straight pipe with constant wall thermal flux in a laminar regime in the presence of a uniform magnetic field. The results showed that adding iron oxide nanoparticles to the base fluid can increase convective heat transfer which is enforced in an applied magnetic field. By adding to nanoparticles concentration, and using stronger applied magnetic field, higher increase in heat transfer coefficient was observed which was thought to be due to changes in thermo physical properties such as thermal conductivity and specific heat capacity.

Aminfar et al. [15] numerically investigated the effect of non-uniform magnetic fields on hydro-thermal and hydro-dynamic behaviors of a ferrofluid flowing throw a vertical pipe in a mixed convection. They used two-phase mixture model to simulate the ferrofluid and they showed that by using a magnetic field with negative gradient in direction of the flow, velocity profile gets flatter and convective heat transfer of the flow increases, while for magnetic fields with positive gradient the opposite is true. They also showed that the effect of magnetic field increases by increasing the field intensity and decreasing Reynold's number.

Furthermore, Aminfar et al. [16] numerically studied the hydro-thermal behavior of a magnetic nanofluid, considering electrical conductivity, in a rectangular vertical duct in the presence of different magnetic fields including non-uniform axial fields (with negative and positive gradient), uniform transverse field and another case when both fields are applied simultaneously, showing that electrical conductivity has significant effects on behavior of ferrofluid which were not negligible. It was also concluded that negative gradient axial field and uniform transverse field have similar effects on increasing the Nusselt number and friction factor, while positive gradient axial field decreases them.

Mohammad pourfard et al. [17] in a numerical investigation and by using a two-phase mixture model studied hydro-thermal characteristics of ferrofluid in a vertical rectangular duct exposed to non-uniform transverse and axial magnetic fields with different magnitudes. The non-uniform transverse magnetic field in their problem was generated by an electric current going through a wire located at a defined distance and parallel to the duct. The results indicated that applying this magnetic field increases the Nusselt number and friction factor, and also creates a pair of vortices that enhances and improves heat transfer. In addition, it was concluded that increase rate of the Nusselt number by applying transverse non-uniform magnetic fields is more than that of the axial