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Hydrothermal assessment of ferrofluids in a metal foam tube under low-frequency magnetic field

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ABSTRACT

In this research, an experimental study is conducted on the hydrothermal characteristics of Fe_3O_4/water ferrofluid flow through a metal foam tube under constant and alternating low-frequency magnetic field. The Nusselt number and friction factor of Fe_3O_4/water ferrofluids are measured and presented at different nanoparticle concentrations, Reynolds numbers, magnetic field intensities as well as frequencies. The results have shown that when the magnetic field intensity and frequency increase, there will be an enhancement in the Nusselt number. A maximum of 36.2% improvement in the Nusselt number of ferrofluid is obtained at $Re = 200$, for 2% nanoparticle weight fraction under alternating magnetic field with 20 Hz frequency. Also, the friction factor of Fe_3O_4/water ferrofluid is observed to be higher than that of DI-water. Moreover, the effect of alternating low-frequency magnetic field is found to be insignificant on the friction factor at the constant magnetic field. The thermal performance index of 1.26 is achieved by applying alternating magnetic field intensity of 400 G with 20 Hz frequency at $Re = 1000$ for the ferrofluid with 2% weight fraction. Finally, a polynomial neural network based on the group method of data handling (GMDH) is established to predict the Nusselt number and friction factor in this study. It is obtained that GMDH-type neural network provides a useful model which can precisely estimate those parameters.

1. Introduction

The development of different technologies such as thermal systems has increased attentions to the heat transfer enhancement methods. Improving heat transfer rates by the application of metallic or non-metallic additives to conventional fluids have been the aim of many investigations. The thermal conductivity of the metallic nanometer-sized particles such as TiO_2, SiO_2, Cu, CuO, Ag and Al_2O_3 is specifically greater than the conventional base fluids at low concentrations which result the improvement of convective heat transfer coefficients [1–6]. Homogeneous and stable suspension of colloidal magnetic nanoparticles in a base fluid is named "ferrofluid". Ferrofluids can be controlled by an external magnetic field. They usually contain magnetic nanoparticles such as Fe_3O_4, Fe_2O_3, FeC, $CoFe_2O_4$, Co or Fe in an appropriate carrier liquid. The interactions between magnetic fields and fluids result in ferrohydrodynamic (FHD), leading to a new field of research in heat transfer enhancement.

Many researchers have studied the effect of using magnetic nanoparticles on the heat and mass transfer of ferrofluids [7–10]. These studies showed that addition of nanoparticles led to a noticeable improvement in convection heat transfer of the base fluids. Moreover, some research studies have been conducted on the evaluation of convection heat transfer of ferrofluids in attendance of constant and alternating magnetic field. Lajvardi et al. [11] and Azizian et al. [12] revealed that by increasing the magnitude of the magnetic field and Fe_3O_4/water ferrofluid concentration, heat transfer coefficients increased remarkably. Motozawa et al. [13] evaluated the impact of magnetic field on heat transfer of Fe_3O_4/water ferrofluid in a rectangular duct, and their results showed that applying magnetic field increased the heat transfer up to 20% in the laminar flow regime. Ghofrani et al. [14] implemented an alternating magnetic field and observed that average heat transfer increased by 27.6% under an alternating magnetic field with high frequency at $Re = 80$. In another study, Hosseinzadeh et al. [15] studied friction factor along with convection heat transfer of Fe_3O_4/water ferrofluid for laminar flow. They showed increasing the Reynolds number, magnetic field intensity and nanoparticle concentration led to heat transfer enhancement. A heat transfer improvement of 19.43% was observed for ferrofluid with 0.2 wt. fraction under 400 G magnetic field at $Re = 2000$. Moreover, they achieved that friction factor increased by the addition of

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Nomenclature

B	magnetic flux density (G)
C_p	specific heat (J/kg K)
D	diameter (m)
$\hat{f}$	estimation function
f	friction factor
fr	frequency (Hz)
h	convective heat transfer coefficient (W/m^2 K)
I	current (I)
L	tube length (m)
M	number of observations
$\dot{m}$	mass flow rate (kg/s)
n	number of inputs
Nu	Nusselt number
P	pressure (kPa)
Q	heat transfer rate (W)
q''	heat flux (W/m^2)
Re	Reynolds number
R^2	absolute fraction of variance
T	temperature (°C)
V	voltage (V)
v	velocity (m/s)
x	axial distance from the inlet of the tube (m)
x_i	inputs
y_i	outputs

Abbreviation

GMDH	group method of data handling
MAE	mean absolute error
RMSE	root mean square error

Greek letters

φ	nanoparticle fraction (%)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa.s)
k	thermal conductivity (W/m K)

Subscripts

bf	base fluid
ff	ferrofluid
m	bulk of the fluid
p	particle
s	surface

nanoparticles inside water and the effect of magnetic field on friction factor of ferrofluids was insignificant. Additionally, another similar experimental study was conducted by Yarahmadi et al. [16], in which applying oscillating magnetic field enhanced the heat transfer up to 19.8% in comparison with no magnetic field condition. However, heat transfer improvement of 24.9% and 37.3% were achieved for Fe_3O_4/water ferrofluid with 2% volume fraction in attendance of constant and alternating magnetic field with 500 G intensity by Goharkhah et al. [17].

In the heat transfer processes, using porous media as heat transfer medium is a method used for improving the convection heat transfer rate. The investigation of hydrodynamics and heat transfer characteristics in porous media has been of considerable interest for engineers and scientists for several decades. In particular, metal foams are widely used thus far in various heat transfer equipment and many researchers have investigated the heat transfer characteristics and hydrodynamics of those structures [18–22]. Some of the researchers have focused on the application of nanofluid through the metal foams. An empirical and numerical investigation was performed on mixed convection flow of alumina nanofluid inside a vertical rectangular metal foam filled channel by Hajipour and Molaei Dehkordi [23]. They showed that there was an increase of 20% in heat transfer performance by adding 0.3% volume concentration of nanofluid, while insignificant change in pressure drop was observed. Xu et al. [24] showed that the increase in nanofluid concentration led to increase in Nusselt number and pressure drop. However, it should be noted that the pressure drop increase was more intensified than the increase of Nusselt number. In another work, Nazari et al. [25] studied the convection heat transfer and pressure loss of alumina nanofluids in a porous metal foam tube with constant wall temperature. The maximum increase in the Nusselt number and pressure drop were about 57% and 39% respectively at $Re = 3704$ for alumina with volume fraction of 1.5%.

Furthermore, the heat transfer characteristics and fluid flow of ferrofluids through porous media in attendance of magnetic field have not been so far investigated extensively. Amani et al. [26] evaluated water-based Fe_3O_4 nanofluid in a metal foam tube and found that the suspension of 2 wt.% nanoparticles inside the water increased the pressure drop and heat transfer rate of the studied nanofluid up to 12.4 and 20.0% at $Re = 1000$, respectively. They applied a constant magnetic field and 23.4% heat transfer improvement was observed [27]. In another study, Amani et al. [28] studied the effect of magnetic field on the MnFe2O4/water nanofluid in a metal foam tube, and the maximum of 16.4% heat transfer improvement was observed under the applied alternating magnetic field. An experimental study was conducted by Sadrhosseini et al. [29] to investigate the heat transfer performance of Fe_3O_4/water ferrofluid flow in a tube filled with the permeable material under the effect of magnetic field. Their results revealed that increasing ferrofluid concentration and Reynolds number led to 50–75% and 19–50% heat transfer improvement respectively. Servati et al. [30] implemented Lattice Boltzmann Method (LBM) and Sheikhnejad et al. [31] employed Brinkman-Darcy equation with local thermal equilibrium approach to study the heat transfer and flow pattern in a partially filled channel with porous media under magnetic field. Sheikhnejad et al. [31] observed an increase of 56% in heat transfer when the Darcy number decreases from 0.1 to 0.001.

To the best knowledge, there is no published study in the literature considering the experimental investigation on hydrothermal analysis of Fe_3O_4/water ferrofluid in a porous metal foam tube in attendance of constant and alternating low-frequency magnetic field and the scarcity of study in this subject is felt strongly in the literature. For this purpose, an experimental investigation is conducted in order to explore the Nusselt number and friction factor of water-based Fe_3O_4 ferrofluid in a metal foam tube in attendance of constant and alternating magnetic field. The Nusselt number and friction factor of Fe_3O_4/water ferrofluid are measured and presented at different nanoparticle weight fractions, Reynolds numbers, and magnetic field intensities and frequencies. The comparison between the results under magnetic field and those with no magnetic field and DI-water is also presented. The thermal performance of the ferrofluids considering the friction factor along with the Nusselt number in one parameter is evaluated and the results are presented. Eventually, two GMDH-type neural network models are implemented for presenting a correlation of Nusselt number and friction factor corresponding to Reynolds number, nanoparticle weight fraction, magnetic field intensity and frequency as inputs.