Applied Thermal Engineering 116 (2017) 329–343

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Convective-heat transfer of magnetic-sensitive nanofluids in the presence of rotating magnetic field

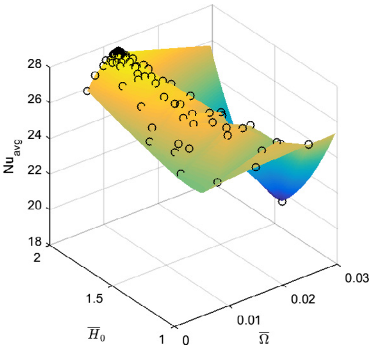
Farzad Fadaei, Asghar Molaei Dehkordi [*], Mohammad Shahrokhi, Zeinab Abbasi

Department of Chemical and Petroleum Engineering, Sharif University of Technology, P.O. Box 11155-9465, Tehran, Iran

HIGHLIGHTS

- Heat transfer of ferrofluids in the presence of rotating magnetic field is studied.
- Influences of magnetic field intensity and frequency are investigated.
- Effect of spin viscosity on the hydrodynamics and heat transfer is examined.
- Optimum average Nusselt number value is evaluated and reported.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 June 2016
Revised 27 November 2016
Accepted 21 January 2017
Available online 23 January 2017

Keywords:
Magnetic field
Magnetic-sensitive nanofluids
Ferrofluids
Heat transfer
Forced convection

ABSTRACT

In this work, forced-convection heat transfer of magnetic-sensitive nanofluids has been investigated in the presence of rotating magnetic field. In this regard, the laminar, Newtonian, incompressible, and two-dimensional (2D) fluid flow in a horizontal duct subject to constant wall temperature boundary condition was modeled. Moreover, the fluid was supposed to be non-electrical conductive and the magnetic field source comprised of two time varying components perpendicular to each other. Influences of magnetic field intensity and frequency, inlet fluid velocity, and spin viscosity on the forced-convection heat transfer of the magnetic nanofluids were investigated. It was found that the applied magnetic field can change the velocity distribution from the parabolic to sinusoidal shape and the average Nusselt number has an optimum value in terms of the magnetic field intensity, frequency, and spin viscosity. For a given magnetic field specification and a fixed ferrofluid, the influence of magnetic field on the Nusselt number value decreases with an increase in the fluid inlet velocity.

1. Introduction

Ferrofluids are colloidal suspensions of single-domain nanoparticles with diameter around 10 nm. In the absence of an external magnetic field, magnetic dipoles of single particles are oriented randomly due to thermal agitation, and the fluid itself does not show any permanent magnetization. On the other hand, when the magnetic nanoparticles are subjected to an external magnetic field, they show magnetic properties [1]. These nanoparticles are usually covered with layers of surfactant to prevent agglomeration of particles due to the Van der Waals and dipole-dipole interactions [2,3]. The surfactant molecules can fill the space between particles and cause steric hindrance, which in turn prevents collision and cohesion of nanoparticles. Therefore, a stable colloidal suspension is formed and the ferrofluid is considered as a homogeneous medium [4,5].

---

[*] Corresponding author.
E-mail address: amolaeid@sharif.edu (A. Molaei Dehkordi).

http://dx.doi.org/10.1016/j.applthermaleng.2017.01.072
1359-4311/

Nomenclature

B	magnetic flux density (T)
C_p	specific heat (J/kg K)
d	channel height (m)
f	frequency (Hz)
g	gravitational acceleration (m/s^2)
H	magnetic field (A/m)
I	moment of inertia per unit mass of MNPs (m^2)
i	imaginary unit
k	thermal conductivity (W/m K)
k_B	Boltzmann constant, (1.38×10^{-23} J/K)
M	magnetization (A/m)
M_d	bulk magnetization (A/m)
Ms	saturation magnetization (A/m)
M_{eq}	equilibrium magnetization (A/m)
Nu	Nusselt number
p	pressure (Pa)
Re	real part
T	absolute temperature (K)
t	time (s)
u	linear axial velocity (m/s)
v	linear velocity (m/s)
V_c	volume of magnetic core (m^3)
x	x coordinate (m)
y	y coordinate (m)

Greek symbols

α	Langevin equation parameter
β	thermal expansion coefficient (1/K)
ζ	Vortex viscosity (Pa s)
η	dynamic viscosity (shear viscosity) (Pa s)
η'	shear spin viscosity (kg m/s)
λ	dilatational viscosity (Pa s)
λ'	bulk spin viscosity (kg m/s)
μ_0	vacuum permeability $4\pi \times 10^{-7}$ (N/A^2, Tm/A)
ρ	density (kg/m^3)
τ	effective magnetization relaxation time constant (s)
φ	MNPs' grains volume fraction in colloidal fluid
χ_0	initial magnetic susceptibility
ω	spin velocity per unit volume of ferrofluid (rad/s)
Ω	radian frequency (rad/s)

Symbols

$\sim$	complex amplitude
–	dimensionless quantity
$*$	complex conjugate
$< >$	average quantity

Momentum and energy transfer in small scales is mainly controlled by diffusion mechanism due to small Reynolds number values. Using the magnetic nanofluids (MNFs) along with applying an external magnetic field is an appropriate way to improve the convective heat transfer. Free-convection heat transfer due to gravity has various applications such as cooling of electronic components [6,7]. By decreasing the system dimensions (characteristic length of the system), this effect decreases drastically. This could be due to dependency of the Rayleigh number value to cubic power of the characteristic length. It may be concluded that this mechanism is not capable of improving heat-transfer rate in small scales. In addition, in aerospace science (in medium with low gravitational acceleration), investigators are exploring to improve the convective heat transfer. Among various methods, convection arising from magnetic field has been found to play an important role in the improvement of convective heat transfer [6,8,9].

Lajvardi et al. [10] investigated forced-convection heat transfer in the presence of magnetic field, in which the water-based MNF composed of Fe_3O_4 nanoparticles with an average size of 10 nm was used. They reported considerable improvement in the heat-transfer coefficient. They discussed that this could be attributed to the higher concentration levels of nanoparticles under applying a uniform field perpendicular to the fluid flow. Recently Ghofrani et al. [11] studied forced-convection heat transfer of MNF in a laminar flow regime subjected to an alternating magnetic field. Their experimental setup composed of a copper tube with the length of 49 cm and diameter of 9 mm. Their results indicate that in the absence of magnetic field, improvement of heat transfer in the regions close to the inlet was more significant compared to the base fluid. Moreover, they reported that applying constant magnetic field at various Reynolds number values affects the heat transfer inversely or had insignificant influence on the heat-transfer coefficient. Finally, under imposing an oscillating field, the average heat-transfer coefficient was found to increase by 26.7% at a Reynolds number value of 80. At higher frequencies, the influence of magnetic field was more significant, however difference between high and low frequencies is slight for large Reynolds number values. Furthermore, it was concluded that alternating magnetic field is more effective for larger volume concentration of nanoparticles.

Azizian et al. [12] investigated the effects of magnitude and gradient of magnetic field on the convective heat transfer of MNFs. They used a number of permanent magnets and various configurations and found that both these parameters are effective in increasing heat-transfer rate. They reported an increased local heat-transfer coefficient up to 4 times, while no significant effect on pressure loss was observed.

Effects of nanofluid on the heat transfer in various geometries such as rectangular shape, cylindrical, cubic, and a cube with internal arrays have been studied by numerous investigators [13–15]. They applied two approaches to study such systems (i.e.; single-phase and two-phase approaches). The single-phase approach requires less computational time and is simpler; however, in this approach the effective properties of nanofluids must be known precisely. These effective physical properties are functions of the properties of both constituents and their concentrations. In this way, one may expect that the classical theory as developed for conventional single-phase fluids such as conservation equations (i.e., momentum, heat, and mass) hold for nanofluids with acceptable approximation.

The two-phase model has been widely used to include the effect of solid-liquid interaction for particles larger than micrometers and millimeters, however, due to the nano-scale size of the particles, the conventional two-phase flow theories for nanofluids must be used with caution particularly for estimating the interaction parameter between two phases. However, in systems with concentration gradient, a two-phase model must be used [16,17].

- **Single-phase approach**

As mentioned earlier, MNF is a mixture of nanoparticles in a base fluid. However, because of the small dimensions of nanopar-