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Effect of different magnetic field distributions on laminar ferroconvection heat transfer in horizontal tube

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ABSTRACT

The forced convection heat transfer of ferrofluid steady state laminar flow through a circular axisymmetric horizontal pipe under different magnetic field is the focus of this study. The pipe is under constant heat flux while different linear axial magnetic fields were applied on the ferrofluid with equal magnetic energy. In this scenario, viscosity of ferrofluid is temperature dependent, to capture ferrofluid real behavior a nonlinear Langevin equation was considered for equilibrium magnetization. For this purpose, the set of nonlinear governing PDEs was solved using proper CFD techniques: the finite volume method and SIMPLE algorithm were used to discretize and numerically solve the governing equation in order to obtain thermohydrodynamic flow characteristics. The numerical results show a promising enhancement of up to 135.7% in heat transfer as a consequence of the application of magnetic field. The magnetic field also increases pressure loss of up to 77% along the pipe; but effectiveness (favorable to unfavorable effect ratio) of the magnetic field as a performance index economically justifies its application such that higher magnetic field intensity causes higher effectiveness of up to 1.364.

1. Introduction

As a member of the broad family of the nanofluids, ferrofluids have found an indispensable importance to a number of industries, mainly due to their vast variety of applications and favorable physiochemical characteristics. Ferrofluids, as colloidal suspensions of magnetized nanoparticles, dispersed in a suitable carrier fluid, have recently become the object of attention of many researchers. This is because of their unique applications such as cooling fluid in loudspeaker core [1], carrier fluids in journal bearing [2], magnetic truck damper [3] and in biological/biomedical applications such as drug delivery vectors, magnetic cell sorting schemes, and magnetocytolysis treatment of localized tumors [4,5].

Prediction the real behavior of ferrofluids and anticipation of its rheological properties has attracted attention of researches: Odenbach [6] showed that due to the Brownian motion of nano-sized particles, ferrofluids are stable under a magnetic dipole–dipole interaction, gravitational force and magnetic field. Shliomis [7] reviewed two basic sets of hydrodynamic equations for magnetic colloids. Considering ferrofluid undergoing simultaneous magnetization and reorientation due to fluid convection, Shliomis [8,9] gave his first magnetization equation. Khushrushahi [10] applied ferrohydrodynamics analysis to extend the fluid flow equation driven by magnetization force and torque on the ferrofluid. Ferrohyrdrodynamics in a uniform and non-uniform rotating magnetic field through modeling and measurements of ferrofluid torque and spin-up flow profiles was studied by He [11]. Rinaldi et al. [12] reviewed the recent advances in magnetic fluid rheology and flows. These include extensions of the governing magnetization relaxation and ferrohydrodynamic equations with a viscous stress tensor that has an antisymmetric part due to spin velocity.

Other studies have targeted heat transfer by means of ferrofluids [13–20]. Remarkable changes in thermophysical properties of ferrofluid were reported as the main reason for the enhancement of heat transfer coefficient by Lajvardi et al. [13] under the influence of an applied magnetic field. Goharkhah and Ashjaee [14] showed that the heat transfer enhancement increases with the magnetic field intensity while an optimum value exists for the frequency of alternating nonuniform magnetic field. The Bénard–Marangoni ferroconvection was investigated by Nanjundappa et al. [15] and Shivakumara et al. [16] where the effect of an increase in the value of magnetic field dependent viscosity is to increase the value of critical stability and in turn delay the onset of Bénard–Marangoni ferroconvection. The numerical results of Aminfar et al. [17] showed that applying magnetic field increases the Nusselt number and friction factor in a vertical rectangular duct and also creates a pair of vortices that enhances heat transfer and prevents sedimentation of nano-particles. Akram et al. [18] presented graphical behaviors of ferrofluid physical parameters. Malvandi and Ganji [19] concluded that in the presence of the magnetic field, the

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Nomenclature

d	particle diameter
P	pressure
C_p	heat capacity
H	magnetic field
B	magnetic flux density
T	temperature
V	velocity vector
u, v	velocity component in z- and r- direction
k_{th}	thermal conductivity
Ma, Mt	hydro-magnetic and Thermo-magnetic number

Greek symbols

ρ	density
η	carrier fluid viscosity
χ	magnetic susceptibility
φ	volume fraction of particle
υ, α	viscous and thermal diffusion

Subscript

ave	averaged
eff	effective value
f	fluid
p	particle
ref	reference value
w	wall

Superscript

*	non-dimensional value

near wall velocity gradients increase, enhancing the slip velocity and thus an increase in heat transfer rate and pressure drop. Finally Abd-Alla et al. [20] studied the effects of both the initial stress and gravity field on the peristaltic flow of an incompressible MHD fluid in a vertical annulus.

To the best of our knowledge, no extensive work has been done for finding the optimum magnetic field distribution in a circular pipe in order to enhance the heat transfer with higher effectiveness as well as its suitability as a performance index.

2. Governing equations

It should be noted that different magnetic field distributions should have a common property. The best practical and physical characteristic for comparison and optimization is the energy consumed to produce these magnetic fields. In accordance with conservation of energy, this consumed energy equals the amount of magnetic energy stored in the magnetic field, and can be determined by calculating the total power delivered by the power source to create the magnetic field. The work done by the electrical current is stored in the inductor as magnetic energy. The change in the total magnetic energy, dE of the inductor is thus equal to

$$dE = L{\cdot}I{\cdot}dI \tag{1}$$

where L is the inductance and I is the electrical current. The total energy stored in the magnetic field of the inductor when the current reaches its final value can be obtained by integrating Eq. (1) between $I = 0$ and $I = I_f$. For a solenoid of volume $\forall = \pi R^2 l$ the self-inductance is equal to

$$L = \mu_0 N^2 \forall \tag{2}$$

where N is the number of wire turn around the coil. The magnetic energy stored in the solenoid is thus equal to

$$E = \tfrac{1}{2} L I_f^2 \tag{3}$$

where $\forall$ is the volume of the solenoid. The magnetic energy can be expressed in terms of B and $\forall$ as follows:

$$E = \frac{(\mu_0 N I_f)^2}{2\mu_0}\forall = \frac{(B)^2}{2\mu_0}\forall \tag{4}$$

where $B = \mu_0 NI$ is the magnetic field in the solenoid and μ_0 is the magnetic permeability of free space. The total magnetic energy of an inductor can now be expressed in terms of the magnetic energy density e which is defined as

$$e = \frac{E}{\forall} = \frac{B^2}{2\mu_0} \tag{5}$$

The magnetic energy stored in the magnetic field is equal to the energy density times the volume. So the total magnetic energy for a constant cross section area, A, can be derived as follows:

$$E = \int \frac{B^2}{2\mu_0} d\forall = \int \frac{B^2}{2\mu_0} A{\cdot}dx \tag{6}$$

Magnetic flux density, B, is related to material magnetization, M, and magnetic field strength, H, by $B = \mu_0(M + H)$ which can be reduced to $B = \mu{\cdot}H$, $\mu = \mu_0(\chi + 1)$ where μ is the permeability of the corresponding media and χ is its susceptibility.

To obtain thermohydrodynamic characteristics of ferroconvection, numerical solution of set of nonlinear coupled PDE of Navier–Stokes, continuity and energy equations, Eq. (7)–(9), is needed. This way, the magnetic force per unit volume is introduced into the momentum equation of fluid motion in an adequate form. The ferrofluid was assumed to be a homogeneous, single phase Newtonian incompressible and non-conductive fluid. Thus the dimensional form of the governing equation for the steady state laminar forced convection ferrofluid flow in a horizontal axisymmetric pipe (Fig. 1) in presence of magnetic field can be written as

Conservation of mass:

$$\nabla{\cdot}(V) = 0 \tag{7}$$

Conservation of momentum:

$$\rho(V{\cdot}\nabla)V = -\nabla P + \mu_0(M{\cdot}\nabla)H + \eta\nabla^2 V \tag{8}$$

Conservation of energy:

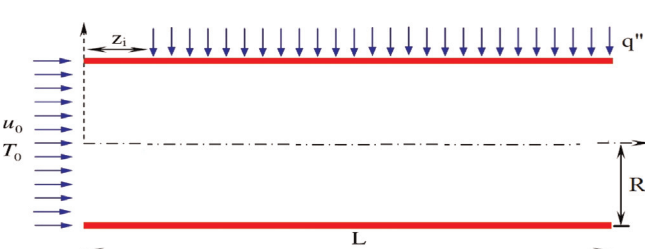

Fig. 1. Schematic geometry of axisymmetric pipe under constant heat flux.