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Research articles

Particle shape effects on ferrofuids flow and heat transfer under influence of low oscillating magnetic field

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ABSTRACT

The purpose of this study is to theoretically examine nanoparticle shapes behavior on mass and heat flow of ferrofluid over a rotating disk with the presence of low oscillating magnetic field. Ferrofluid is prepared by water and iron nanoparticles of three different shapes like sphere, oblate ellipsoid and prolate ellipsoid. The problem has been formulated by employing the controllable force into the fundamental hydrodynamic equations and its effect along with particle shape factor on physical properties of fluid is discussed. These equations are converted into a system of ordinary differential equations by employing appropriate similarity approach and then solved by HAM based Bvph2 package. Effects of particle shape, particle volume fraction and magnetization parameter on axial, radial and tangential velocities along with temperature profile are demonstrated through graphically. The results for local Nusselt number are calculated and analyzed and the path for enhancement in heat transfer is also proposed.

1. Introduction

Fluids which can be effectively controlled by magnetic fields of moderate strength are a challenging subject for scientists interested in the basics of fluid mechanics as well as for application engineers. The research to introduce a controllable force into the fundamental hydrodynamic equations opens a fascinating field of new phenomena. Due to the fact that no natural liquids offer these features, its difficult chemical make-up requires distinct knowledge in chemistry and colloidal physics to synthesize new and improved liquids and to modify the basic properties of the suspensions. Thus, the overall field of ferrofluid research has a highly interdisciplinary character, bringing chemists, experimental physicists, engineers, theoretical physicists, applied mathematicians and physicians together.

Due to the fact that no natural liquids offer these features, Neuringer and Rosensweig [1] were the first to suggest a set of equations of motion for ferrofluids, which have been expansively developed by Shliomis [2] and have remained the basis for most subsequent research on ferrofluids. Lately, many studies have been done to investigate the characteristic of ferrofluid through different particle of fluctuating shapes, sizes and structures [3–9]. Although the relationship amongst shape and magnetization is not as straight, the impact of different geometries on magnetic properties keeps on being assessed. De Vicente et al. [10] prepared magnetite rod-like particles with average diameter and length of 560 nm and 6.9 μm , respectively. These works showed that magneto-rheological performance is significantly improved for elongated magnetic particles under small-amplitude shear and simple steady shear flows, hence suggesting that particle shape strongly affects the structuration under an external field. In another study [11], magneto-rheological performances of magneto-rheological fluids was investigated by using iron particles of different shapes like spherical, plate-like, and rod-like and found beater improvement by non-spherical particles. In heat transfer point of view, Ellahi et al. [12] discussed the particle shapes effects on heat transfer rate and fluid flow of nanofluid. Their fallouts show that heat transfer rate can be improved through taking different shapes of particles. In another study, R. Ellahi et al. [13] instigated theoretical study on ferrofluid by taking spherical nanoparticles. They found 7.86% heat-transfer enhancement in the absence of a magnetic field and found 8.73% heat-transfer enhancement in present of a magnetic field. Sheikholeslami and Bhatti [14] also discussed Various shapes of nanoparticles effect on forced convective heat transfer and fund highest rate of heat transfer by Platelet shape under constant magnetic force. In their another studies [15,16], the methods to enhance heat transfer by means of Coulomb force and Fe_3O_4 nanoparticles are deliberated. A numerical study on the heat

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Nomenclature

$\mathbf{V}$	velocity
v_r, v_θ, v_z	velocity components
r, θ, z	cylindrical coordinates
T	temperature of fluid
$\boldsymbol{M}$	magnetization of fluid
$\boldsymbol{H}$	strength magnetic field
C_p	specific heat
τ_s	relaxation time parameter
α_v	stretching parameter
ε	temperature ratio
τ_B	Brownian relaxation time
μ_0	permeability of free space,
$\boldsymbol{I}$	moments of inertia of the particles
t	time
n	number of particles
m	magnetic moment of the particle
μ	viscosity
υ	kinematic viscosity
φ	volume fraction
$\boldsymbol{\omega}_{\mathbf{p}}$	internal angular momentum of particles
p	pressure
k	thermal conductivity
$\boldsymbol{\Omega}$	vorticity of the flow
$\mathbf{M}_o$	instantaneous magnetization
ω_o	the angular frequency of field
ξ_o	amplitude of the magnetic field
S	unsteadiness parameter
Pr	Prandtl number
Br	rotational Brinkman number
Re	rotational Reynolds number
ρ	density

Subscripts

int	cluster
s	solid particle
f	base fluid
a	aggregation
c	backbone particles
nc	dead ends particles
nf	composition of particles and base fluid

transfer of ferrofluids in microchannels was conducted by Xuan et al. [17]. They finally concluded that heat-transfer rate could increases if the directions of magnetic field gradient and fluid flow are the same. In addition, role of nanoparticles under magnetic field in heat transfer applications should be investigated to design a process that is efficient and environmental friendly. It is remarkable that there are still only relatively few such publications [18,19]. To apply the ferrofluid to practical heat transfer processes, more studies on its flow and heat transfer feature are needed.

In present study, effects of particle shapes, particle size and oscillating magnetic field on fluid flow and heat transfer over rotating stretchable disk are demonstrated. To achieve this goal, the present work is organized in the following way. In mathematical formulation section, a controllable force is introduced into the fundamental hydrodynamic equations and correlation models that support to effective physical properties are formulated. The solution for problem and accuracy of method is discussed in solution of the problem section. The impact of pertinent flow quantities on velocity and temperature profiles as well as on local Nusselt number are demonstrated and discussed in results and discussion section. Last section, achievements of study is concluded and gives a way to enhance the convective heat transfer in fluid flow.

2. Mathematical formulation

2.1. Flow modeling

Consider the axially symmetric laminar and non-conducting flow of an incompressible nano-Ferrofluid past a stretchable rotating disk that has an angular velocity varying with time ($\Omega_v/1-\beta_v t$). The coordinate system and geometry of the problem are shown in Fig. 1. We consider that the disk rotation speed has a form of $\Omega_v r/1-\beta_v t$ and the disk stretching velocity is $\alpha_v \Omega_v r/1-\beta_v t$, which is proportional to the radius r.

The basic governing equations containing continuity, motion, temperature, magnetization and rotational motion equations in vector form are

$$\nabla.\mathbf{V} = 0 \tag{1}$$

$$\rho_{nf}\frac{d\mathbf{V}}{dt} = -\nabla p + \mu_{nf}\nabla^2\mathbf{V} + \mu_0(\boldsymbol{M}.\nabla)\boldsymbol{H} + \frac{1}{2\tau_s}\nabla\times(\boldsymbol{\omega}_{\mathbf{p}} - \boldsymbol{\Omega}) \tag{2}$$

$$(\rho C_p)_{nf}\frac{dT}{dt} = k_{nf}\nabla^2 T \tag{3}$$

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{\omega}_{\mathbf{p}}\times\boldsymbol{M} - \frac{1}{\tau_B}(\boldsymbol{M} - \boldsymbol{M}_0) \tag{4}$$

$$\boldsymbol{I}\frac{d\boldsymbol{\omega}_{\mathbf{p}}}{dt} = \boldsymbol{M}\times\boldsymbol{H} - \frac{1}{\tau_S}(\boldsymbol{\omega}_{\mathbf{p}} - \boldsymbol{\Omega}) \tag{5}$$

here, $\mathbf{V} = (v_r, v_\theta, v_z)$ is velocity, T is temperature, $\boldsymbol{M}$ is magnetization of the fluid, $\boldsymbol{H}$ is strength magnetic field, $\boldsymbol{M}_0$ is instantaneous magnetization, τ_s is Relaxation time parameter, τ_B is Brownian relaxation time, μ_0 is permeability of free space, $\boldsymbol{I}$ is sum of moments of inertia of the particles per unit volume, $\boldsymbol{\omega}_{\mathbf{p}}$ is internal angular momentum due to the self-rotation of particles and $\boldsymbol{\Omega}$ is the vorticity of the flow.Since, τ_s is small, the inertial term is negligible in comparison with relaxation term i.e., $\boldsymbol{I}\frac{d\boldsymbol{\omega}_{\mathbf{p}}}{dt} \ll \boldsymbol{I}\frac{\boldsymbol{\omega}_{\mathbf{p}}}{\tau_s}$, therefore, Eq. (5) can be written by way of

$$\boldsymbol{\omega}_{\mathbf{p}} = \boldsymbol{\Omega} + \frac{\tau_s}{\boldsymbol{I}}(\boldsymbol{M}\times\boldsymbol{H}) \tag{6}$$

Now, Eqs. (2) and (4) in view of Eq. (6) can written as

$$\rho_{nf}\frac{d\mathbf{V}}{dt} = -\nabla p + (\boldsymbol{M}.\nabla)\boldsymbol{H} + \mu_{nf}\nabla^2\mathbf{V} + \frac{1}{2}\nabla\times(\boldsymbol{M}\times\boldsymbol{H}) \tag{7}$$

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{\omega}\times\boldsymbol{M} - \frac{1}{\tau_B}(\boldsymbol{M} - \boldsymbol{M}_0) + \frac{\tau_s}{I}\boldsymbol{M}\times(\boldsymbol{M}\times\boldsymbol{H}) \tag{8}$$

Magnetic torque $\boldsymbol{M}\times\boldsymbol{H}$ and viscous torque $(\boldsymbol{\Omega} - \boldsymbol{\omega}_{\mathbf{p}})$ are acting on the particles and equilibrium of both torques, which leads to the hindrance of the particle rotation, can thus be written from the Eq. (6) as

$$\boldsymbol{M}\times\boldsymbol{H} = -6\mu_{nf}\phi(\boldsymbol{\omega} - \boldsymbol{\Omega}_{\mathbf{p}}) \tag{9}$$

In the existence of slow oscillating magnetic field Eq. (8) can be written as [13]

$$\tau_B\frac{dR(\xi_e)}{dt} = \left(1 - \frac{1}{2}\left(\frac{1}{L_e} - \frac{1}{\xi_e}\right)\xi_o R(\xi_e)\cos\omega_0 t\right) \tag{10}$$

In above, the parameters ω_o and ξ_o are frequency and amplitude of the real magnetic field whereas the effective Langevin function is donated as parameter L_e.