Engineering Science and Technology, an International Journal 21 (2018) 439–450

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

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

Full Length Article

Convection in a magnetic nanofluid saturating a porous medium under the influence of a variable gravity field

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ARTICLE INFO

Article history:
Received 17 November 2017
Revised 7 March 2018
Accepted 28 March 2018
Available online 4 April 2018

2010 MSC:
76E06
76E25
76S05

Keywords:
Convection
Magnetic nanofluids
Porous media
Darcy model
Magnetic field
Variable gravity

ABSTRACT

This paper presents a numerical investigation of the onset of instability in a thin magnetic nanofluid (or ferrofluid) layer saturating a porous medium, subject to a gravity field which varies with distance across the layer. A model that accounts for the effect of Brownian diffusion, thermophoresis, magnetophoresis and Darcy's law is considered. We employed the Chebyshev pseudospectral method and QZ algorithm to obtain the numerical solutions. The impact of important parameters, which affect the instability of the system has been analyzed at the onset of convection for water-based and ester-based magnetic nanofluids. The results indicate that increase in the width of magnetic nanofluid layer (d), Langevin parameter (α_L), gravity coefficient (δ), permeability parameter (K); and decrease in the Lewis number (Le), concentration Rayleigh number (R_n), modified diffusivity ratio (N_A), nonlinearity of fluid magnetization (M_3) is to delay the onset of convection.

1. Introduction

Fluids that are produced by dispersing nanometer-sized particles (nanoparticles) into heat transfer liquids (like water, oils, glycols, and fluorocarbons) are known as the nanofluids. The nanoparticles are generally made up with metals, carbon nanotubes, or oxides. Nanofluids show much better heat transfer characteristics as compared to traditional heat transfer fluids, like water, oil, ethylene glycol etc. Nanofluids have its importance in electronic applications, transportation, industrial cooling applications, heating buildings and reducing pollution, cooling of nuclear systems, defense and space, mass transfer enhancement, energy storage, solar absorption, friction reduction, biomedical applications etc. [1]. Experimental investigations on convection heat transfer in nanofluids were organized by many researchers and a noticeable improvement in heat transfer rates of nanofluids was found. An enhancement in the thermal conductivity is another attractive feature of nanofluid. In an experimental work, Eastman et al. [2] observed a significant increase (about 40%) in the thermal conductivity of ethylene glycol–based nanofluid. The area *heat transfer through porous medium* has various engineering applications related to ground water pollution, geothermal energy recovery, flow through filtering media, crude oil extraction, and thermal energy storage. One of the applications of nanofluid in porous media is the cooling of microchannel heat sinks which are used for electronic cooling [3]. Study of mixed convection in a porous medium subject to an applied magnetic field is also significant due to its various applications in petroleum and geothermal reservoirs, thermal insulation, etc. Buongiorno [4] conducted a detailed study of the convective transport in nanofluids by considering seven different slip mechanisms that can generate a relative velocity between the base fluid and nanoparticles. The author reported that the Brownian motion and thermophoresis are the two most significant nanoparticles slip mechanism. He introduced a new model for the transport phenomena in nanofluids by considering the effects of Brownian diffusion and thermophoresis. Nield and Kuznetsov [5] were the first to study the onset of instability in a horizontal layer of a porous medium saturated by a nanofluid on the basis of the model suggested by Buongiorno [4]. They investigated this problem for both non-oscillatory as well as oscillatory convection. Further, they developed a new model (see Nield and

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Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2018.03.016
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Nomenclature

c_f	Nanofluid specific heat
c_p	Nanoparticle specific heat
d	Thickness of the nanofluid layer
D_a	Darcy number
D_B	Brownian diffusion coefficient
D_H	Magnetophoretic diffusion coefficient
D_T	Thermophoretic diffusion coefficient
$\mathbf{g}$	Acceleration due to gravity
H	Magnetic field
$\mathbf{k}$	Unit vector in the z-direction
k_1	Thermal conductivity
k_B	Boltzmann's constant
K	Permeability of porous medium
Le	Lewis number
$\mathbf{M}$	Magnetization
M_s	Magnetic saturation
M_1, M_1', M_2, M_2'	Magnetic parameters
M_3	Nonlinearity of fluid magnetization
N_A, $N\prime_A$	Modified diffusivity ratios
N_B	Modified particle density increment
p	Pressure
P_r	Prandtl number
Ra	Thermal Rayleigh number
Rn	Concentration Rayleigh number
t	Time
T	Temperature
T_c	Temperature at the upper surface
T_h	Temperature at the lower surface
$\mathbf{q}$	Filtration velocity of the nanofluid
V_a	Vadasz number

Greek symbols

α	Coefficient of thermal expansion
α_L	Langevin parameter
β	Uniform temperature gradient
κ	Thermal diffusivity
μ	Viscosity of nanofluid
μ_0	Magnetic permeability of vacuum
ρ	Density
δ	Gravity coefficient
θ	The perturbation in temperature
ϕ	Nanoparticle volume fraction
ϕ_0	Reference value for nanoparticle volume fraction
χ	Tangent magnetization susceptibility
χ_2	Chord magnetization susceptibility
ϵ	Porosity

Subscripts

b	Basic state
f	Fluid
m	Porous medium
0	Reference quantity

Operators

∇	$\frac{\partial}{\partial x}+\frac{\partial}{\partial y}+\frac{\partial}{\partial z}$
∇^2	$\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$
∇_1^2	$\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$

Kuznetsov [6]) by introducing a more realistic boundary condition for the nanoparticle fraction. The authors show that the oscillatory convection cannot occur with the new boundary conditions. For more studies in the area of nanofluid convection; see, e.g., [7–11] and references therein.

Nowadays, studying magnetic field effects on fluids becomes an important active area of research due to its uncountable applications in various fields, such as in chemistry, physics, engineering science etc. In the area of medicine, various significant applications of the variable magnetic field are presented by Sieroń and Cieślar [12]. Magnetic nanofluids (MNFs) belong to a distinctive class of nanofluids that exhibit both fluid as well as magnetic characteristics. A special feature of these nanofluids is that they are easy to manipulate with the use of an external magnetic field. In many of the applications, the ability to manipulate the fluid motion in porous media, without direct access to the fluid is desirable. These applications include controlled the positioning of liquids or chemicals treatment, positioning of geophysically imageable liquids into appropriate zones for subsequent imaging [13]. A laboratory-scale experimental study of the flow of ferrofluids in porous media was organized by Borglin et al. [13]. Another experimental and theoretical investigation of the motion of multiphase fluids comprising paramagnetic nanoparticles in porous media was conducted by Ryoo et al. [14]. For more related studies, the reader is referred to [15,16].

A primary study of convective instability of a ferromagnetic fluid under the presence of a uniform magnetic field was conducted by Finlayson [17]. The author reported that for a horizontal ferromagnetic fluid layer (about 1 mm thick), the magnetic mechanism dominates over the gravitational buoyancy mechanism. He showed that the applied magnetic field plays a significant role in controlling magnetic convection which is significant in ferrofluid technology. Vaidyanathan et al. [18] analyzed the thermoconvective instability in a ferromagnetic fluid saturated porous layer, subject to a uniform magnetic field. They derived an exact solution for two free boundaries which are flat and concluded that the oscillatory convection cannot occur. The authors also reported that the presence of porous medium enhances the effect of magnetization. A non-linear investigation of the instability in a magnetized ferrofluid saturated a porous layer was performed by Sunil and Mahajan [19]. They applied a generalized energy method and demonstrated a coupling between the magnetic and buoyancy forces. Some other related studies have also been carried out by [20–25]. Sheikholeslami Kandelousi [26] investigated the natural convection heat transfer for a Fe_3O_4-water nanofluid under the influence of an external variable magnetic field. The author considered constant heat flux boundary conditions and reported a decrease in the heat transfer enchantment as the value of Rayleigh number and Magnetic number increase. However, an increase in the heat transfer enhancement is reported as the value of Hartmann number increases. Sheikholeslami and Rashidi [27] studied the mixed convection heat transfer for Fe_3O_4 water nanofluid by considering magnetic field dependent viscosity under the influence of a non-uniform external magnetic field. Ismael et al. [28] investigated the mixed convection in a Cu-water nanofluid inside a square cavity subjected to an external magnetic field and a constant heat flux. The authors considered the partial slip effects along the lid-driven horizontal walls and reported that strength and orientation of magnetic field plays a significant role in controlling the convection. Rashad et al. [29] studied the steady laminar two-dimensional mixed convection for a Cu-water nanofluid under the influence of an applied magnetic field. A numerical investigation of mixed convection Cu-water nanofluid in a square cavity filled with a Darcian porous medium subject to an external