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Slip flow of magnetite-water nanomaterial in an inclined channel with thermal radiation

Z. Abbas*, T. Rahim, J. Hasnain

Department of Mathematics, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan

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ABSTRACT

An analytic study is performed to analyze the mixed convective two phase flow of magnetite-water (ferrofluid) and viscous fluid in an inclined channel with velocity slip at the walls in the presence of thermal radiation. The channel, separated in two phases, is suffused with a viscous fluid in upper phase and an electrically conducting ferrofluid in the lower phase. Fully developed flow conditions are considered while developing the flow equations. The obtained ordinary differential equations are solved using an analytic approach named as Perturbation method. The numerical values of the results are plotted to interpret the influence of numerous pertinent parameters on flow fields. The results show an increase in the fluid velocity with the hike in velocity slip parameters whereas the fluid velocity decreases with an increase in ferroparticles volume fraction. It is also found that the radiation reduces the impact of natural convection by reducing the temperature difference between the fluid and the walls of the channel.

1. Introduction

In the recent times, innovative nanotechnology has drawn attention of many researchers since it delivers different prospects to design and manufacture products with effective heat transfer enhancements. Heat transfer efficiency of fluids can be improved by adopting several approaches, for example changing the boundary conditions, flow geometry or by augmenting thermal conductivity of the conventional liquids. One of the methods to enhance the thermal conductivity of conventional base fluids like water, oil, kerosene and ethylene glycol mixture is inclusion of ultrafine nanoparticles (100 nm diameter) in these fluids. Since solid possesses higher thermal conductivity as compared to heat transfer fluid, so introduction of minimum possible ($< 1\%$) volume fraction of nanoparticles [1,2] in base fluid can be fruitful to obtain beneficial thermal properties. Fersadoua et al. [3] investigated the effects of magnetic field and porous medium on the entropy generation and mixed convection flow of Newtonian fluid in a vertical channel in the absence of viscous dissipation. Das et al. [4] presented closed form solutions for the flow of electrically conducting nanofluid with three different nanoparticles in the region between two parallel plates. A special class of nanoparticles is also available named as ferroparticles (magnetic particles). Manganese zinc ferrite ($Mn - ZnFe_2O_4$), cobalt ferrite ($CoFe_2O_4$) and magnetite (Fe_3O_4) are few magnetic particles which when added to the base fluid also exhibit the magnetic properties of solid. The magnetic properties of the ferrofluids are more effective under the influence of magnetic field as each particle comes into contact with a force which is shifted to the connected liquid phase. Ferrofluids carry applications in several engineered systems and devices like rotating anode X-ray generators, viscous dampers for gravity gradient satellites, vacuum chambers in semi-conductor industry, energy conversion devices, novel pumps, accelerometers and in high speed computer disk devices to remove deleterious dust particles. Goharkhah and Ashjaee [5] performed heat transfer analysis of ferrofluid with magnetite in a horizontal channel with forced convection and varying magnetic field. Gul at al. [6] studied the vertical channel flow of ferrofluid with heat transfer under the effect of magnetic field analytically.

Natural convection is one of the modes to transfer the thermal energy and has great significance in various industrial domains as well as technical applications. Nuclear reactors, thermal management in electronic instruments, chemical vapor deposition reactors are few applications that entail natural convective flow between heated parallel plates. Minimal installation and maintenance expense in low heat producing electronic gadgets make this process more advantageous. But if we deal with higher operating temperatures and space technology, radiative heat transfer along with natural convection can play a significant role. Fire research, heating and cooling of channels and aeronautics are few areas of research in which combined convective and radiative heat flow occur. Gupta and Gupta [7] studied the radiative flow of a viscous fluid inside a vertical channel in the vicinity

* Corresponding author.
E-mail address: za_qau@yahoo.com (Z. Abbas).

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Nomenclature

B_0	magnetic field, [T]
b	ratio of coefficient of thermal expansion of phases, $[=\beta_2/\beta_1]$, $[-]$
b_i	velocity slip lengths
C_p	specific heat at constant pressure, [J kg^{-1} K^{-1}]
Ec	Eckert number, $[=\bar{u}_1^2/C_p(T_{w1}-T_{w2})]$
Gr	Grashof number, $[=g\beta_1 h_1^3(T_{w_1}-T_{w_2})/\nu_1^2]$
g	acceleration due to gravity, $[LT^{-2}]$
h_i	heights of the phases, [L]
h	ratio of heights of phases, $[=h_2/h_1]$ $[-]$
κ_i	thermal conductivity of fluids of phases, $[Wm^{-1}K^{-1}]$
k	ratio of coefficient of thermal conductivity of fluids of phases, $[=K_1/K_2]$ $[-]$
k^*	mean absorption coefficient
M	Hartman number, $[=B_0h_2\sqrt{\sigma/\mu_2}]$
m	ratio of coefficient of dynamic viscosity of phases, $[=\mu_1/\mu_2]$ $[-]$
n	ratio of densities of fluids of phases $[=\rho_2/\rho_1]$, $[-]$
P	nondimensional pressure gradient, $[-]$
Pr	Prandtl number, $[\mu_1C_p/K_1]$ $[-]$
q_r	radiation heat flux
Re	Reynolds number, $[-]$
Rd	radiation parameter $[=R_2/R_1]$ $[-]$
T_i	temperature of the fluid of phases, [K]
T_{w_i}	temperature at the surfaces of the plates of the phases, [K]
u_i	velocity of phases x-direction, $[ms^{-1}]$
$\bar{u}_1$	average velocity, $[ms^{-1}]$
u_i^*	dimensionless velocities of phases, $[ms^{-1}]$
x, y, z	spatial coordinates, $[m]$
y_i^*	dimensionless variables

Greeks letters

α_i	thermal diffusivities of the phases, $[m^2s^{-1}]$
β_i	coefficient of thermal expansion, $[K^{-1}]$
γ_i	velocity slip parameters of the phases, $[kgm^{-1}s^{-1}]$
μ_i	dynamic viscosities of the phases, $[-]$
ν_i	kinematic viscosities of the phases, $[m^2s^{-1}]$
ρ_i	fluid densities of the phases $[kgm^{-3}]$
θ_i	dimensionless temperatures of the phases, $[(T-T_{w_2})/(T_{w_1}-T_{w_2})]$ $[-]$
ϕ	angle of the channel with horizontal, $[rad]$
σ_2	electrical conductivities of fluid, $[sm^{-1}]$
σ^*	Stefan-Boltzmann
φ	nanofluid volume fraction $[-]$
ε	$[=PrEc]$

Subscripts

w	surface conditions
i	for phase I $i=1$, for phase II $i=2$, for nanofluid $i=nf$, for nanoparticles $i=s$

of magnetic field. Sanyal and Samanta [8] analyzed the radiation effect on combined force and free convection of steady laminar flow of viscous fluid in a vertical channel. Chauhan and Kumar [9] performed a theoretical study to examine the radiation and viscous effects on the flow of viscous fluid inside a channel saturated with porous medium. Hayat et al. [10] considered the three-dimensional flow of viscous fluid bounded by two horizontal plates and studied the radiation effects on the incompressible fluid. Prakash and Muthtamilselvan [11] numerically investigated the radiative effects on fully developed flow of incompressible micropolar fluid through a vertical channel in the presence of strong magnetic field.

The situation regarding multi-phase flow and heat transfer phenomena of immiscible fluids seems to have an exceptional importance in chemical and nuclear industries. Petroleum industry, plasma physics and geophysics also involve certain processes where immiscible fluids flow. Two-fluid model is the simplest model which we encounter most during petroleum transport and extraction. Two-phase flow occurrence in many industrial sectors, nature and bio-fluids make this flow phenomenon much thoughtful for engineers and scientists. Food manufacturing, steam generators and condensers, spray casting, blood flow, refrigeration, mud and air flow are few applications that also involve two-phase flow. Flow of immiscible fluids between two parallel plates has been studied by several researchers with different flow geometries. Shail [12] studied the Hartmann flow of an electrically conducting fluid flowing between a layer of non-conducting fluid and an insulating wall of the channel. Lohrasbi and Sahai [13] extended the problem of [12] and presented the analytical solution as well as numerical solution. Malashetty and Leela [14] investigated the heat transfer characteristics of horizontal two-phased system of electrically conducting fluids between two infinite plates. An approximate solution by using perturbation method for the two-phase flow of viscous fluids streaming between two parallel inclined plates was presented by Malashetty and Umavathi [15]. Kumar et al. [16] examined the free convection flow of two-fluid continuum model through vertical channel by considering micropolar and viscous fluids and presented analytical solution. Abbas et al. [17] performed an analytical analysis to explore the magnetic effects on the two-phase flow of viscous and couple stress fluids in an inclined channel. The porosity effects on mixed convective flow of a third grade fluid and a viscous fluid flowing through an inclined channel under the effect of external magnetic field were studied numerically by Hasnain et al. [18].

The aim of present study is to discuss a theoretical analysis of two-phase flow of magnetic ferrofluid and viscous fluid in an inclined channel. The slip boundary conditions are assumed at both upper and lower walls but magnetic field of uniform strength is applied only in lower phase. Heat transfer is also investigated with addition of mixed convection mode and thermal radiation effects. Analytical solutions of formulated coupled ordinary differential equations are constructed using method of successive approximation upto order one.

2. Problem formulation

Let us consider two infinite parallel plates, making an inclined channel, placed parallel to $xz-$ plane. The plates are inclined at an angle ϕ with horizontal axis and separated by a distance h_1+h_2 with the temperature being different but constant. The channel is divided in two phases by an interface layer at $y=0$ between a viscous fluid and an electrically conducting water based ferrofluid with magnetite as ferroparticles. The upper phase named as Phase I ranging from 0 to h_1 contains a viscous fluid and lower phase labeled as Phase II ranging from 0 to $-h_2$ carries a ferrofluid. Both the fluids are immiscible, incompressible and have densities ρ_i, viscosities μ_i, electrical conductivities σ_i, thermal conductivities K_i, thermal diffusivities α_i and specific heat capacitance C_{p_i} where $i=1$ is for viscous fluid, $i=nf$ is for ferrofluid and $i=2$ is for base fluid. The thermophysical properties of ferrofluid are provided in Table 1. A homogeneous external magnetic field of intensity B_0 is applied transverse to the flow direction. An agent that stimulates the fluid to flow through the channel is a constant pressure gradient. The physical model of the problem is shown in Fig. 1. Under these suppositions the momentum and energy equations for both fluids are expressed as

Phase-I