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Buoyancy effects on nanofluid flow past a convectively heated vertical Riga-plate: A numerical study

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ABSTRACT

The main concern here is to study nanofluid flow past a vertical Riga-plate subjected to convective heating. Riga-plate is composed of span wise aligned array of electrodes and permanent magnets fixed on a plane surface. This arrangement induces Lorentz force parallel to the array which decays exponentially with distance normal to the plate. Practically useful assumption of zero normal wall mass flux is imposed. Traditional transformations give rise to the locally similar equations which are treated numerically by shooting approach. MATLAB built-in package bvp4c, based on collocation method, is also implemented for generating numerical results. Results show that velocity distribution parallel to the plate is enhanced due to the inclusion of Lorentz force. Drag reduction is anticipated in the case of opposing flow, which is important in engineering applications. Temperature and wall heat flux are increasing functions of convective heating parameter (Biot number). For assisting flow regime, temperature drops when either the wall-parallel Lorentz force or buoyancy forces become stronger. Heat flux from the plate is not affected with the variation in Brownian diffusion coefficient. Moreover, highest heat transfer rate is achieved for the situation in which thermophoretic effect is absent.

Contents

1. Introduction

Limited thermal characteristics of conventional fluids restricts their suitability for modern applications requiring a high level performance while maintaining reduced size of the thermal systems such as for cooling of microchips in computer processors, mircoelectromechanical systems (MEMS) and to obtain fast transient regimes in heating systems. Nanofluids refer to the suspensions of ultrafine particles (typically 1–100 nm in diameter) in pure liquid carriers. Eastman et al. [1] dispersed carbon nanotubes in pure water and observed that thermal conductivity of resulting nanofluids is doubled. The remarkable thermal transport of nanofluids make them promising for widespread heat transfer applications involving micro manufacturing, refrigeration, automotives, heat exchangers, aircrafts and space applications and other high energy devices. Detailed review papers by Das et al. [2], Wang and Mujumdar [3], Kakac and Pramuanjaroenkij [4], Wong and Leon [5], Saidur et al. [6] and Sidik et al. [7] summarize the benefits of nanofluids in practical applications and discuss their usage in futuristic applications. The significance of different thermal conductivities in nanofluid plane wall jet problem is outlined in Turkyilmazoglu [8]. The ordinary fluid correlations cannot forecast the increased heat transfer coefficient which exceeds the

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Nomenclature

x, y, z (m) Cartesian coordinate system
u, v, w (m s^{-1}) velocity components in the $x-, y-$ and $z-$ directions respectively
T (K) local nanofluid temperature
k_f(W/m K) thermal conductivity of base fluid
u_∞ (m s^{-1}) ambient fluid velocity
T_∞ (K) ambient fluid temperature
T_f (K) convective surface temperature
h_f (W/m^2 K) heat transfer coefficient associated with the convection fluid
g (m/s^2) acceleration due to gravity
j_0 (A/m^2) current density
M_0 (Tesla) magnetization of permanent magnets
p (m) width of magnets and electrodes
Nu_x local Nusselt number
D_B Brownian diffusion coefficient
D_T thermophoretic diffusion coefficient
Gr_x local Grashof number
Bi Biot number
Re_x local Reynolds number
C_f skin friction coefficient
Sc Schmidt number
Nb Brownian motion parameter
$s(\eta), f(\eta)$ dimensionless velocity and nanoparticle concentration
Nr buoyancy ratio parameter
Z modified Hartman number
d parameter related to width of magnets and electrodes
Pr Prandtl number
Nt thermophoretic parameter
$t_1,\ t_2,\ t_3$ unknown initial conditions to be determined

Greek symbols
ϕ_∞ ambient nanoparticle concentration
υ_f (m^2/s) kinematic viscosity of the base fluid
ρ_f (kg/m^3) density of the base fluid
ρ_{f_∞} (kg/m^3) density of the quiescent fluid
ρ_p (kg/m^3) density of nanoparticles
β (K^{-1}) thermal expansion coefficient
τ_w (kg/m s^2) wall shear stress
α_f (m^2/s) thermal diffusivity of base fluid
τ ratio of effective heat capacity of the nanoparticle material to that of base fluid
η similarity variable
$\theta(\eta)$ dimensionless temperature
λ mixed convection parameter
ϕ local nanoparticle concentration

normal thermal conductivity effects. Buongiorno [9] considered nanofluid velocity as the sum of base fluid velocity and the relative velocity of nanoparticles which he referred as the slip velocity. He analyzed seven slip mechanisms and discovered that only Brownian diffusion and thermophoresis have significant role when turbulence effects are absent. Nanofluid flow due to convectively heated vertical surface was studied by Aziz and Khan [10] using Buongiorno model. Khan et al. [11] employed Buongiorno model to address nanofluid flow over a horizontal plate immersed in a uniform free stream. Later, nanofluid flow due to exponentially deformable surface was analyzed by Mustafa et al. [12] using Buongiorno model. Analytical approximations for nanofluid flow bounded by a non-linearly deforming surface were obtained by Rashidi et al. [13]. Buongiorno model for natural convection flow of nanofluid near a vertical plate was discussed by Kuznetsov and Nield [14,15] using passive condition for nanoparticle concentration Dinarvand et al. [16] explored the mixed-convective stagnation point flow of nanofluid by incorporating diffusiophoresis mechanism in Buongiorno model. Turkyilmazoglu [17] analytically explored the Buongiorno two-phase model for the condensation of nanofluid film flow. Rashidi et al. [18] provided comparative study of single phase and two-phase models for nanofluid heat transfer through a wavy channel. In another paper, Rashidi et al. [19] carried out Lie Group analysis for free convection in nanofluid flow through a porous space with chemically reacting species. Garoosi et al. [20] employed Buongiorno model to examine the natural convection nanofluid flow in heat exchangers. In recent past, various contributions in this direction are made (see [21–29] and refs. therein.)

Gailitis and Lielausis [30] developed an innovative mechanism to produce wall-parallel Lorentz force. The proposed device was the electromagnetic actuator consisting of electrodes and permanent magnets scaled on a plane surface. This setup is referred as Riga-plate which is highly beneficial since it prevents the boundary layer separation and lessens turbulence effects which in turn diminishes the pressure drag and friction in submarines. Tsinober and Shtern [31] examined the stability of Blasius flow over a Riga-plate using the Lorentz force term proposed by Grinberg [32]. The Grinberg term is decoupled from the flow and it decays exponentially normal to the plate. Also, Ahmad et al. [33] discussed nanofluid flow adjacent to a vertical permeable Riga-plate under the assumption of strong wall suction. Series solutions for small Brownian motion and thermophoresis parameter were also developed which were shown to be consistent with the numerical results. Entropy generation analysis of nanofluid flow adjacent to a Riga-plate was recently reported by Abbas et al. [34].

Present study is mainly motivated towards the mixed convective nanofluid flow bounded by a convectively heated vertical Riga-plate. Grinberg term, representing the Lorentz force due to plate's own electromagnetic field is considered. Both aiding and opposing mixed convection situations are analyzed. By means of usual transformations, locally similar equations are formulated which are treated by a convenient shooting method. Local similarity solution of the problem enables one to analyze the impact of parameters at fixed location from the plate. Such kind of solution has been frequently obtained in the past for numerous boundary layer flow problems (see for instance [35–40] and refs. therein). For verification, MATLAB package bvp4c is also utilized to derive numerical solutions. The influence of pertinent parameters on the flow fields is described through graphical illustrations. Expressions of wall drag coefficient and local Nusselt number, which are of high interest in industrial applications, are evaluated and discussed.

2. Mathematical model

Consider the nanofluid flow past a vertical infinite Riga-plate with u and v representing velocity components in x- and y-directions respectively where the coordinate x extends along the plate and y is normal to it. A surface parallel Lorentz force is induced due to electromagnetic field of the Riga-plate. This force decays exponentially with the distance normal to the plate. The fluid far from the plate is characterized by $u_\infty(x) = ax$ where