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Radiation effects on stagnation point flow with melting heat transfer and second order slip

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ABSTRACT

This article examines the effects of melting heat transfer and thermal radiation in stagnation point flow towards a stretching/shrinking surface. Mathematical formulation is made in the presence of mass transfer and second order slip condition. Numerical solutions to the resulting nonlinear problems are obtained by Runge-Kutta fourth fifth order method. Physical quantities like velocity, temperature, concentration, skin friction, Nusselt and Sherwood number are analyzed via sundry parameters for stretching/shrinking, first order slip, second order slip, radiation, melting, Prandtl and Schmidt. A comparative study with the previously published results in limiting sense is made.

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Introduction

There is no doubt that stagnation point flows through different aspects have already been studied extensively. This is because of importance of such flows in several areas of aerospace technology and engineering. In fact Hiemenz [1] made pioneering research for stagnation point flow of viscous fluid. Later the stagnation point flows are examined by the various authors for viscous and non-Newtonian fluids. Even many recent attempts have been made for the analysis of such flows. For instance, Hayat et al. [2] studied the stagnation point flow of second grade fluid over a stretching surface with heat and mass transfer. Rosali et al. [3] considered unsteady mixed convection stagnation point flow by a heated vertical surface embedded in a porous medium. The two-dimensional stagnation point flow of viscous fluid toward a convectively heated stretching/shrinking sheet is examined by Bachok et al. [4]. Dinarvand et al. [5] developed the similarity solution for the MHD unsteady stagnation point flow with buoyancy effect. Sharma et al. [6] numerically discussed the MHD stagnation point flow of viscous fluid towards a stretching/shrinking permeable plate. Rashidi and Erfani [7] employed Pade-approximation for MHD Hiemenz flow in presence of variable wall temperature and porous medium. Turkyilmazoglu and Pop [8] constructed exact analytical solutions for stagnation point flow of Jeffrey fluid over a stretching/shrinking surface. Bhattacharyya [9] analytically discussed the stagnation point flow past a stretching/shrinking surface with first order chemical reaction. The unsteady stagnation-point flow towards a shrinking/stretching sheet with time dependent surface temperature is analyzed by Bhattacharyya [10] while Makinde, et al. [11] used Adomian decomposition method for boundary layer flow with thermal radiation past a moving vertical porous plate.

In all the aforementioned investigations, the no-slip conditions are employed. However it is noted in a micro electro mechanical system and some coated surfaces (such as Teflon, resist adhesion) the no-slip boundary condition is inadequate. Especially partial slip condition is important in the situation when the fluid is particulate such as emulsions, suspensions, foams and polymer solutions. Undoubtedly the materials exhibiting slip are important in technological applications such as in the polishing of artificial heart valves and internal cavities. A number of models have been proposed for describing the slip effect that occurs at solid boundaries. The slip flow model describes a relation between the tangential component of the velocity at the surface and the velocity gradient normal to the surface. Thus a new dimension is added to the above mentioned study by considering the effects of partial slip at the stretching wall. Few researchers have already focused to the flow and heat transfer analysis at micro-scale with slip effects. Turkyilmazoglu

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Nomenclature

a, c	constants	$\delta,\ \gamma$	first/second order slip parameters
f	similarity function for velocity	C_f	skin friction coefficient
Pr	Prandtl number	Re_x	local Reynolds number
Sc	Schmidt number	Me	melting parameter
ε	stretching/shrinking parameter	Nu_x	local Nusselt number
Sh_x	local Sherwood number	u_e	external flow velocity [ms^{-1}]
u	velocity in x direction [ms^{-1}]	u_w	stretching velocity [ms^{-1}]
v	velocity in y direction [ms^{-1}]	η	similarity independent variable
x	coordinate along the plate [m]	y	coordinate normal to the plate [m]
θ	dimensionless temperature	R	radiation parameter
μ	dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]	α	thermal diffusivity [$m^2\ s^{-1}$]
ρ	fluid density [$kg\ m^{-3}$]	q_r	radiative heat flux [$kg\ m^{-2}$]
c_p	specific heat [$m^2\ s^{-2}\ K^{-1}$]	k^*	absorption coefficient
ψ	stream function [$m^2\ s^{-1}$]	ν	kinematic viscosity [$m^2\ s^{-1}$]
T_w	surface temperature [K]	k	thermal conductivity [Wm^{-1} K]
T_∞	ambient temperature [K]	q_w	heat flux [Wm^{-2}]
C_∞	concentration far away from sheet	C_w	wall concentration

[12] found the multiple solutions for the heat and mass transfer effects in MHD flow of viscoelastic fluid over a stretching wall with slip boundary condition. Freidoonimehr et al. [13] analyzed the MHD stagnation point flow towards a porous rotating sheet with velocity slip condition. Turkyilmazoglu [14] investigated the heat and mass transfer characteristics in MHD viscous flow over a permeable stretched surface with velocity and thermal slip conditions. Mukhopadhyay [15] performed an analysis to study the slip effects in MHD boundary layer flow over a porous stretching sheet with thermal radiation. Malvandi [16] examined the stagnation point flow of nanofluid over a stretched surface with Navier's slip condition. Mabood et al. [17] considered melting heat transfer on MHD flow of nanofluid with radiation and second order slip. The slip effect in mixed convective boundary layer flow over a flat surface is studied by Bhattacharyya et al. [18]. Rashidi et al. [19] studied the effects of magnetohydrodynamic in flow by a rotating disk with slip effect. Mukhopadhyay [20] examined the MHD axisymmetric flow of a viscous fluid by a stretched cylinder with heat transfer and partial slip effect. Flow of second-grade fluid past a stretching sheet with partial slip is addressed by Hayat et al. [21].

To the best of our information, the stagnation point flow towards a surface with simultaneous effects of melting heat transfer and second order slip are not discussed so far. The purpose here is to fill this gap. Hence both cases of flows induced by stretching and shrinking surface velocities are discussed. Thermal radiation and mass transfer characteristics in the flow are present. Numerical solution to the resulting nonlinear flow problem is computed. Comparison of presents results with the previous limiting studies is also made.

Problem development

We consider the effect of melting heat transfer in stagnation point flow of viscous fluid towards a stretching surface with second order slip. The stretching and external flow velocities are taken respectively by $u_w = cx$ and $u_e = ax$ (where a and c are a positive constant). It is also assumed that viscous dissipation and heat generation or absorption effects are absent. Thermal radiation features are present. The melting surface and the ambient temperatures are respectively denoted by T_m and T_∞ where $(T_\infty > T_m)$. Mass transfer is also considered and the species concentration is sustained at the prescribed constant value C_w at the sheet. The governing equations of mass, linear momentum, energy and concentration are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = u_e\frac{du_e}{dx} + \nu\frac{\partial^2 u}{\partial y^2}, \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}, \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2}, \tag{4}$$

with the boundary conditions

$$y = 0:\ u = u_w + u_{slip},\ T = T_m,$$
$$k\left(\frac{\partial T}{\partial y}\right)_{y=0} = \rho(\lambda + c_s(T_m - T_0))v(x,0),\ C = C_w, \tag{5}$$

$$y = \infty:\ u = u_e,\ T = T_\infty,\ C = C_\infty. \tag{6}$$

In above expressions u and v are the velocity components along the x and y-axes respectively. $\alpha = k/\rho c_p$ is the thermal diffusivity, ν is the kinematic viscosity, ρ is the density of the fluid, T is the temperature, q_r is the radiative heat flux, c_p is the specific heat at constant pressure and D is the diffusion coefficient. Through Roseland approximation one can write

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y}, \tag{7}$$

in which σ^* denotes the Stefan–Boltzmann constant and k^* the absorption coefficient. Expanding T^4 about T_∞ and neglecting higher order terms one arrives at

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^* T_\infty^3}{3\rho c_p k^*}\frac{\partial^2 T}{\partial y^2}. \tag{8}$$

The velocity slip defined in study [2] is

$$u_{slip} = \frac{2}{3}\left(\frac{3-\alpha_1 l^3}{\alpha_1} - \frac{3}{2}\frac{1-l^2}{K_n}\right)\lambda\frac{\partial u}{\partial y} - \frac{1}{4}\left(l^4 + \frac{2}{K_n^2}(1-l^2)\right)\lambda^2\frac{\partial^2 u}{\partial y^2}$$
$$= A\frac{\partial u}{\partial y} + B\frac{\partial^2 u}{\partial y^2}. \tag{9}$$

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