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Impact of heat generation/absorption and homogeneous-heterogeneous reactions on flow of Maxwell fluid

Muhammad Ijaz Khan [a], Tasawar Hayat [a, b], Muhammad Waqas [a], Muhammad Imran Khan [c, *], Ahmed Alsaedi [b]

[a] Department of Mathematics, Quaid-I-Azam University 45320, Islamabad 44000, Pakistan
[b] Nonlinear Analysis and Applied Mathematics (NAAM) Research Group, Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80257, Jeddah 21589, Saudi Arabia
[c] Heriot Watt University, Edinburgh Campus, Edinburgh EH14 4AS, United Kingdom

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ABSTRACT

Heat absorption/generation and homogeneous-heterogeneous reactions effects in stagnation point flow of rate type fluid towards moving sheet with nonlinear velocity and variable thickness are addressed. Radiation and viscous dissipation effects are ignored. A simple isothermal model of homogeneous-heterogeneous reactions is used to regulate the temperature of high melting surface. Thermodynamic processes of homogeneous-heterogeneous reactions analyze the effect of temperature phase changes, such as melting and evaporation. Computations for strong nonlinear systems are presented after non-dimensionalization. The behaviors of different involved variables on the velocity, temperature and concentration fields is studied in detail. The major outcome of the present study is that heat transfer rate decreases under the considerable effects of melting parameter and Prandtl number Pr. It is also observed that velocity field increases for larger melting parameter as well as Deborah number. It is observed that velocity of the fluid particle enhances for larger Deborah number. Further, lower Prandtl fluids have higher thermal conductivities contributing faster diffusion of heat in thicker thermal boundary layer structure when compared with higher Prandtl fluids in thinner boundary layer region.

1. Introduction

Investigations regarding chemical reaction have achieved continuous consideration from the recent engineers and scientists. These reactions are notable in several procedures like chemical processing, hydrometallurgical industry, fibrous insulation, atmospheric flows, damage of crops because of freezing, water and air pollutions, production of ceramics and polymer, and fog formation and dispersion. Obviously the reactions can be mentioned through heterogeneous and homogeneous processes. Specific examples of these processes may include biochemical systems, combustion and catalysis. Note that heterogeneous processes arise in limited region or inside the boundary of a phase however homogeneous processes occurs consistently in the whole given phase. Merkin [1] initially provided the concept of heterogeneous and homogeneous processes by considering the stretched flow of viscous liquid over flat surface. He examined the homogeneous reaction through cubic autocatalysis while first order process is considered for heterogeneous reaction. His analysis shows that surface reaction dominates in the neighborhood of the leading edge of plate. Numerical solution for stretched flow of viscous liquid in presence of heterogeneous and homogeneous processes is calculated by Chaudhary and Merkin [2]. Khan and Pop [3] investigated stretched flow of viscoelastic liquid with heterogeneous and homogeneous processes. Analysis provided in Ref. [3] is further extended by Kameswaran et al. [4] by considering nanoparticles. Shaw et al. [5] addressed the effectiveness of heterogeneous and homogeneous processes in the flow of micropolar liquid induced by permeable stretched/shrinked surface. Stagnation point flow of viscous liquid considering heterogeneous and homogeneous processes is developed by Bachok et al. [6]. Further recent investigations regarding heterogeneous and homogeneous processes can be mentioned through Refs. [7–15].

Most of the researchers showed attention to a great extent on heat transfer problems related to solidification or melting effects. Processes comprising the melting heat phenomenon in non-Newtonian liquids have significant demands in thermal engineering including oil extraction, thermal insulation, magma solidification,

* Corresponding author.
E-mail addresses: mikhan@math.qau.edu.pk (M.I. Khan), mk42@hw.ac.uk (M.I. Khan).

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recovery of geothermal energy, melting of permafrost, and silicon wafer process. Effectiveness of melting characteristics in laminar flow towards flat surface is presented by Epstein and Cho [16]. Analysis reported in Ref. [16] has been reported by several researchers under different physical aspects. For instance, impact of viscous dissipation and melting characteristics in convective flow of magneto nanoliquid with second order slip is presented by Mabood et al. [17]. Awais et al. [18] modeled and examined the stretched flow of Burgers material in presence of stagnation point and melting heat. Influences of inclined MHD and melting heat in stagnation point flow of viscous nanoliquid in the vicinity of stagnation point is addressed by Gireesha et al. [19]. Singh and Kumar [20] explored heat absorption and melting effects in stagnation point flow of micropolar material. Das et al. [21] disclosed the salient features of melting effects in stretched flow of Jeffrey material. Characteristics of heterogeneous and homogeneous processes and melting effects in flow of viscous material over stretching surface with variable thickness is disclosed by Hayat et al. [22]. Hayat et al. [23,24] presented the impact of melting and magnetohydrodynamic (MHD) effects in stretched flow of viscous and Williamson nanoliquids. Heterogeneous/homogeneous and melting characteristics in flow of viscous nanoliquid is scrutinized by Hayat et al. [25]. Some studies on heat transfer rate are given in Refs. [26–30].

The objective of present paper is to analyze the effects of melting heat transfer and homogeneous-heterogeneous reactions in the stagnation point flow of rate type fluid towards a moving sheet having variable thickness. The theme here is to venture further for the homogeneous-heterogeneous regime in flows induced by nonlinear stretching sheet with variable thickness. The representative results are obtained for velocity, temperature, concentration distributions. Local heat transfer rate is computed. The governing boundary layer equations are transformed to ODEs and then solved by Homotopy analysis method (HAM). Homopoty analysis method [31–40] is the powerful technique to attain the covergence of series solutions. The relevant results are displayed and analyzed.

2. Formulation

We consider two-dimensional stagnation point flow of rate type fluid in the presence of heat absorption/generation. The thickness of the variable sheet is defined by $y = A_1(x+b)^{\frac{1-n}{2}}$. Acceleration/retardation of stretched surface greatly depends upon the shape of variable sheet thickness. The velocity of the external flow is $u \to U_e(x) = U_\infty(x+b)^n$ and the velocity of the stretched surface is $u = U_w(x) = U_0(x+b)^n$. Temperature of the melting surface is T_m while the temperature of the free stream surface is T_∞. A basic homogeneous-heterogeneous reaction model is initially used by Merkin [1]:

$$A^* + 2B^* \to 3B^*, \quad rate = k_c a_1 b_1^2.$$

On the catalyst surface, single, isothermal and first order reaction is

$$A^* + B^* \to 3B^*, \quad rate = k_s a_1.$$

Both reaction procedures are assumed isothermal. In isothermal reaction, the temperature of entire system remains consistent. In above equations k_1 and k_s indicates the rate constants while a_1 and b_1 denote the concentrations of chemical species A^* and B^*. Flow investigation under consideration has the expressions [10,13,14]:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_e\frac{dU_e}{dx} + \lambda U_e^2\frac{\partial^2 U_e}{\partial x^2} - \lambda\left(u^2\frac{\partial^2 u}{\partial x^2} + v^2\frac{\partial^2 u}{\partial y^2} + 2uv\frac{\partial^2 u}{\partial x \partial y}\right), \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho c_p}(T - T_m), \tag{3}$$

$$u\frac{\partial a_1}{\partial x} + v\frac{\partial a_1}{\partial y} = D_A\frac{\partial^2 a_1}{\partial y^2} - k_1 a_1 b_1^2, \tag{4}$$

$$u\frac{\partial b_1}{\partial x} + v\frac{\partial b_1}{\partial y} = D_B\frac{\partial^2 b_1}{\partial y^2} + k_1 a_1 b_1^2, \tag{5}$$

$$u = U_w(x) = U_0(x+b)^n, T = T_m \text{ at } y = A_1(x+b)^{\frac{1-n}{2}}, \tag{6}$$

$$D_A\frac{\partial a_1}{\partial y} = k_s a_1, D_B\frac{\partial a_1}{\partial y} = -k_s a_1 \text{ at } y = A_1(x+b)^{\frac{1-n}{2}}, \tag{7}$$

$$u \to U_e(x) = U_\infty(x+b)^n, T \to T_\infty, \quad a_1 \to a_0, \quad b_1 \to 0, \text{ when } y \to \infty, \tag{8}$$

$$k\left(\frac{\partial T}{\partial y}\right)_{y=A_1(x+b)^{\frac{1-n}{2}}} = \rho\left[\lambda_1 + c_s(T_m - T_0)\right] v(x,y)_{y=A_1(x+b)^{\frac{1-n}{2}}}, \tag{9}$$

where velocity component u is along x direction and velocity component v is along y direction, λ viscoelasticity of Maxwell fluid, U_e free stream velocity, U_w stretching velocity, T temperature, ρ density, c_p specific heat, Q_0 heat generation/absorption coefficient, T_m melting temperature, D_A and D_B diffusion species coefficients of A and B, k_1 rate constant, a_0 positive dimensional constant, k_s heat transfer coefficient, T_∞ ambient temperature, U_0 and U_∞ reference velocities, λ_1 latent heat of fluid and T_0 fixed or initial temperature and c_s heat capacity of the solid surface (Table 1).

Taking [22]:

$$\psi = \sqrt{\frac{2}{n+1}\upsilon U_0(x+b)^{n+1}}F(\xi), \xi = \sqrt{\frac{n+1}{2}\frac{U_0}{\upsilon}(x+b)^{n-1}}y,$$

$$u = U_0(x+b)^n F'(\xi), v = -\sqrt{\frac{n+1}{2}\upsilon U_0(x+b)^{n-1}}\left(F(\xi) + \eta\frac{n-1}{n+1}F'(\xi)\right), \tag{10}$$

$$\theta(\xi) = \frac{T - T_m}{T_\infty - T_m}, g(\xi) = \frac{a_1}{a_0}, h(\xi) = \frac{b_1}{a_0}, T = T_m + \theta(T_\infty - T_m), \tag{11}$$

continuity Eq. (1) holds identically. Eqs. (2) – (5) take the form:

$$F''' + FF'' - \frac{2n}{n+1}F'^2 + \beta\begin{bmatrix}(3n-1)FF'F'' \\ -\frac{2n(n-1)}{n+1}F'^3 \\ +\xi\frac{n-1}{2}F'^2F'' \\ -\frac{n+1}{2}F^2F'''\end{bmatrix} + \frac{2n}{n+1}A^2 + 2\beta\frac{n(n-1)}{n+1}A^3 = 0, \tag{12}$$

$$\Theta'' + \Pr F\Theta + \frac{2}{n+1}\gamma\Pr\Theta = 0, \tag{13}$$

Table 1
Series solutions convergence when $\alpha = 0.3, M = 0.5, \Pr = 0.8\beta = 0.3\gamma = 0.01n = 0.9Sc = 1.2K = 0.5Ks = 1A = 0.1$.

Order of approximations	$-f''(0)$	$-\theta'(0)$	$-g'(0)$
1	0.69100	0.51520	0.43699
5	0.86046	0.42088	0.54275
10	0.86983	0.41455	0.54353
15	0.86787	0.42271	0.54246
25	0.86131	0.43100	0.54095
30	0.86131	0.43100	054095