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Heat transfer of a magnetohydrodynamic fluid-saturated porous medium over a permeable non-isothermal stretching sheet

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ABSTRACT

The study of flow and heat transfer of a magnetohydrodynamic viscous fluid-saturated porous medium, past a permeable and non-isothermal stretching sheet with internal heat generation or absorption and radiation is analyzed. Closed-form solutions to the full Darcy-Brinkman equations, without applying boundary layer approximations, are found using a similarity transformation. We propose to find closed-form solutions for temperature corresponding to the thermal conditions, which are quadratic function of the distance from the origin. The temperature functions for heating conditions are given in terms of Kummer's functions. Asymptotic expressions of the temperature functions are also presented valid for both large and small modified Prandtl numbers. The effect of viscosity ratio, suction parameter, porous parameter is studied.

Keywords: Magnetohydrodynamic viscous fluid, saturated porous medium, stretching sheet, Kummer's functions, Asymptotic expressions

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INTRODUCTION:

An interesting fluid mechanics application is found in polymer extrusion processes where the object on passing between two closely placed solid blocks is stretched into a liquid region. The stretching imparts a unidirectional orientation to the extrudate, thereby improving mechanical properties. The liquid is basically meant to cool the stretching sheet whose property as a final product depends greatly on the rate at which it is cooled. It is important to consider two important aspects in this physically interesting problem: proper choice of cooling liquid and regulation of the flow of the cooling liquid, due to the stretching sheet, to achieve a desired rate of cooling appropriate for successfully arriving at a sought final product. Flow and heat transfer from a linearly stretching sheet gained more importance due to practical applications in industrial processes. In most of the investigations involving heat transfer, we observe that either the constant prescribed surface temperature (PST) or constant prescribed wall heat flux (PHF) boundary condition is assumed. It is a well-known fact that constant PST and PHF assumed by many are difficult to realize. Also if the final product that is obtained after cooling needs to be non-uniform in terms of properties, variable PHF is the appropriate temperature boundary condition.

Heat generation or absorption may become important in weak-electrically conducting polymeric liquids due to the non-isothermal situation they are in and also due to the presence of cation/anion salts dissolved in them. An example of such a liquid is polythene oxide.

The transfer of heat, mass and momentum in the laminar boundary layer flow on a heated stretching sheet are considered important from both theoretical and practical point of view. Such situations may arise often in polymer processing industry, liquid thin film development and other related surface flows. Sakiadis [6] studied first the boundary layer flow over a continuous solid surface moving in its own plane with a constant speed. It is generally assumed that the sheet is inextensible. But many cases arises in polymer industry in which it is necessary to deal with a stretching sheet as noted by Crane [2]. Gupta and Gupta[3] presented the heat and mass transfer over a stretching sheet with blowing or suction.

Kumari, M and Takhar, HS and Nath, G [4] studied about the flow and heat transfer over a stretching sheet with a magnetic field in an electrically conducting fluid using numerical methods. Subhas and Veena [8] studied heat transfer characteristics in the laminar boundary layer flow of a visco-elastic fluid over a linearly stretching continuous surface with variable wall temperature subjected to suction or blowing and obtained solution in terms of kummer’s function. Siddheshwar and Mahabaleshwar [7] studied the MHD flow and also heat transfer in a viscoelastic liquid over a stretching sheet in the presence of radiation. The stretching of the sheet is assumed to be proportional to the distance from the slit. Vajravelu and Nayefh [11] presented the flow and heat transfer by introducing temperature dependent heat source or sink. They considered heat transfer in a saturated porous medium over a continuous impermeable stretching surface with power law surface temperature (PST) and power law surface heat flux (PHF) including the effects of fractional heat and internal heat generation or absorption. Many authors including Ranjagopal et al., [5] Anjalidevi S.P. and Thiyarajan M [1], Sujit Kumar Khan et. al., [9] have analyzed the problem on boundary layer flow due to the stretching sheet/continuous moving sheet for different flow models and boundary conditions. Swain et al[10] studied the steady two dimensional stagnation point flow of an incompressible conducting viscous fluid with variable properties over a stretching surface embedded in a saturated porous medium using shooting method

In all the stretching sheet problems (both hydro-dynamic and hydromagnetic) mentioned earlier, radiation effect has not been considered. We know that the radiation effect is important under many non-isothermal situations. If the entire system involving the polymer extrusion process is placed in a thermally controlled environment, then radiation could become important. In this paper, we consider the effect of radiation, magnetic field and temperature dependent heat source over a stretching sheet, with variable PST/PHF.

2. MATHEMATICAL FORMULATION

2.1 Flow analysis

A two-dimensional flow of incompressible viscous fluid saturated in a porous medium part a permissible stretching sheet $y=0$ in the presence of a magnetic field $\vec{B}$ is considered. The fluid is occupied above the sheet $y>0$. The axis is chosen perpendicular to the stretching sheet. The flow is generated by the application of two equal and opposite forces along the stretching sheet, keeping the origin fixed. The continuity and momentum equations for a steady, two dimensional fluid saturated porous medium in the presence of a weak magnetic field of strength B_0 are

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

$$\rho_f\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\hat{\mu}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\mu}{k_1}\varphi u \tag{2}$$

$$\rho_f\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\hat{\mu}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\mu}{k_1}\varphi v \tag{3}$$

where u, v and p are the velocity component in the x-direction , velocity component in the y-direction, and pressure. The physical quantities ρ_f , ϕ , $\hat{\mu}$, μ and k_1 are the density of the fluid , porosity, effective viscosity , permeability and magnetic field respectively and they are all assumed to be constants.

We assume that the flow is subjected to suction on the sheet with constant transverse velocity v_0 and the sheet is stretching with a constant rate $c>0$.

The relevant boundary conditions are

$$u=u_W=cx,\ v=-v_0,\ p=p_W \text{ at } y=0, \tag{4}$$

$$u\to 0 \text{ as } y\to\infty \tag{5}$$

Where u_W and p_W are the longitudinal velocity component and the pressure specified at the sheet respectively.

We introduce a similarity transform for velocity component and pressure as,

$$u=cxf'(\eta)\ ,\ v=-\left(\frac{c\mu}{\rho_f}\right)^{1/2} f(y)\ ,$$

$$p=p_W-\frac{1}{2}\frac{c\mu}{\phi}g(\eta) \tag{6}$$

with $\eta=\left(\frac{c\rho_f}{\mu}\right)^{1/2} y$.

Using equation (6) into equation (2) and equation (3), we get

$$f'^2-ff''=\Lambda f'''-Kf', \tag{7}$$

$$ff'=\frac{1}{2}g'-\Lambda f''+Kf \tag{8}$$

and

$$f(0)=R\,,\ f'(0)=1\,,\ g(0)=0\,,\ f'(\infty)\to 0 \quad (9)$$

where $\Lambda=\dfrac{\hat{\mu}}{\mu}$ is the viscosity ratio,

$K=\dfrac{\phi\,\mu}{k_1\rho_f c}$ is the porous parameter,

$R=\dfrac{v_0}{\left(\dfrac{c\mu}{\rho_f}\right)^{1/2}}$ is the suction parameter.

The solution of equation (7) subject to equation (9) can be obtained as,

$$f(\eta)=A+Be^{-m\eta}, \quad (10a)$$

where $m=\dfrac{A+\sqrt{A^2+4\Lambda k}}{2\Lambda}$,

$$A=\frac{(1+2k)R+\sqrt{R^2+4\Lambda(\Lambda+K)}}{2(1+K)},$$

$$B=\frac{-2\Lambda}{R+\sqrt{R^2+4\Lambda(\Lambda+K)}} \quad (10b\text{-}d)$$

$g(\eta)$ can be obtained by integrating equation (8) and using equation (9) as

$$g(\eta)=f^2+2\Lambda f'-2K\int_0^{\eta} f d\eta-2\Lambda-R^2 \quad (11)$$

The solution for velocity component and pressure are given by,

$$u=-Bme^{-m\eta}cx \quad (12)$$

$$v=-\left(\frac{c\mu}{\rho_f\mu_w^2}\right)^{1/2}\left(A+Be^{-m\eta}\right) \quad (13)$$

$$\varphi=P_w-\frac{1}{2}c\mu\Bigg\{\left(A+-Be^{-m\eta}\right)^2 -2\Lambda\left(Bme^{-m\eta}\right)+2(K+H)\left(A\eta-\frac{Be^{-m\eta}}{m}\right) -2\Lambda-R^2+2K\frac{R}{m}\Bigg\} \quad (14)$$

The dimensionless skin friction at the sheet can be calculated form,

$$C_f=\frac{\tau_w}{\rho_f u_w^2}=\Lambda\,\mathrm{Re}_x^{-1/2}\,f''(0) \quad (15)$$

where $f''(0)=Bm^2$ is the dimensionless velocity gradient,

$\mathrm{Re}_x=\dfrac{\rho_f u_w x}{\mu}$ is the local Reynolds number.

Case (i) :Very Large Suction R>>1

We expand equation (10.b) to equation (10.d) into a two-term approximations where $R>>1$, respectively as follows,

$$A\sim R+\frac{\Lambda}{R}\,, \quad (16)$$

$$B\sim-\frac{\Lambda}{R}+\frac{\Lambda^2(1+K)}{R^3}, \quad (17)$$

$$m\sim\frac{R}{\Lambda}+\frac{(1+K)}{R} \quad (18)$$

and find

$$f''(0)=Bm^2=-\frac{R}{\Lambda}-\frac{(1+K)}{R}+O\left(R^{-3}\right) \quad (19)$$

Case(ii): Very large injection , $R=-R^*$ and $R^*>>1$

In this case,

$$A\sim-\frac{K}{1+K}R^*+\frac{\Lambda}{R^*}, \quad (20)$$

$$B\sim\frac{4\Lambda^2(1+K)}{R^{*3}}, \quad (21)$$

$$m\sim\frac{1+K}{R^*}-\Lambda\frac{(1+K)^2}{R^{*3}}+2\Lambda^2\frac{(1+K)^3}{R^{*5}} \quad (22)$$

And the dimensionless velocity gradient is given by,

$$f''(0)=-\frac{(1+K)}{R^*}-\frac{2\Lambda(1+K)^2}{R^*3}+O\left(R^{-5}\right) \quad (23)$$

2.2 Heat transfer analysis

The steady 2-D energy equation for a porous medium with internal heat generation on or absorption in the presence of radiation is governed as

$$\left(\rho C_p\right)_f \phi\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_m\left(u\frac{\partial^2 T}{\partial x^2}+v\frac{\partial^2 T}{\partial y^2}\right)$$
$$+Q_m\left(T-T_\infty\right)+\frac{16\sigma_m^* T_\infty^3}{3k_m^*}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (24)$$

where T is the temperature of the mixture and T_∞ is the temperature far from the sheet. The physical quantities C_p, k_m, Q_m, σ_m^* and k_m^* are the specific heat at constant pressure, thermal conductivity, volumetric rate of internal heat generation or absorption, the Stephan–Boltzmann constant and the mean absorption coefficient, respectively and they are all assumed to be constants for simplicity. The subscripts m and f denote the properties belonging to the mixture.

Two thermal boundary conditions are considered, for example, the prescribed surface temperature condition (PST) and prescribed surface heat flux condition (PHF).The boundary conditions are

$$T=T_W=T_\infty+Dx \ \ (PST) \quad (25)$$

$$q_W=-k_m\frac{\partial T}{\partial y}=Ex \quad (PHF) \quad (26)$$

$$T\to T_\infty \ \text{ as } \ y\to\infty \quad (27)$$

where T_W is the wall temperature, q_w is the wall heat flux and D and E are proportional constants.

Case(i) **The Prescribed Surface Temperature (PST) case**

In PST case we introduce a transformation for the temperature

$$\theta=\frac{T-T_\infty}{T_W-T_\infty}\Rightarrow T=\theta(\eta)Dx+Ex^2+T_\infty$$
$$=\varphi(x,\eta)+T_\infty=x\theta_1(\eta)+x^2\theta_2(\eta)+T_\infty \quad (28)$$

where η is defined in Equation (6). Substituting Equations (6), (10) and (24) into Equations (20), (21) and (23) yields

$$(1+Nr)\theta_1''+P\left(A-\frac{e^{-m\eta}}{m}\right)\theta_1'+P\alpha\theta_1=0 \quad (29)$$

$$\theta_1(0)=1,\theta_1(\infty)\to 0 \quad (30)$$

where

$Nr=\frac{16\sigma_m^* T_\infty^3}{3k_m^* k_m}$ is the radiation parameter,

$P=\frac{c_p\,\hat{\mu}\phi}{k_m}$ is the Prandtl number and

$\alpha=\frac{Q_m}{\phi(\rho c_p)_f}$ is the internal heat parameter.

Using, $\xi=\frac{PBe^{-m\eta}}{m(1+Nr)}$, Equations (25) and (26) are transformed to,

$$\xi\theta_1''+\left(\frac{p^*A}{m}-\xi\right)\theta_1'+\frac{\alpha p^*}{\xi}\theta_1=0 \quad (31)$$

$$\theta\left(\frac{p^*B}{m}\right)=1, \qquad \theta(0)=0 \quad (32)$$

where the primes stand for differentiation with respect to ξ and $P^*=\frac{P}{1+Nr}$ is the modified Prandtl number.

After further transformation, the solution of Equation (31) subject to Equation (32) can be solved, in terms of Kummer's function as,

$$\theta_1(\xi)=\left(\frac{m\xi}{P^*B}\right)^{p+q}\frac{M\left(p+q-1,2q+1,\xi\right)}{M\left(p+q-1,2q+1,\frac{P^*B}{m}\right)} \quad (33)$$

where

$$p=\frac{P^*A}{2m},\quad q=\sqrt{\frac{P^*A^2-4P^*\alpha}{2m}}, \quad (34)$$

and

$$M(a,b,z) = 1 + \sum_{n=1}^{\infty} \frac{(a)_n z^n}{(b)_n n!} \quad (35)$$

is the Kummer's function,

$$(a)_n = a(a+1)(a+2)....(a+n-1) = \frac{\Gamma(a+n)}{\Gamma(a)}$$

Where, $\Gamma(a)$ is the Gamma function.

The solution of equation (33) in terms of η is

$$\therefore \varphi(x,\eta) = x\left\{ (e^{-m\eta})^{p+q} \frac{M\left(p+q-1, 2q+1, \frac{P^* B e^{-m\eta}}{m}\right)}{M\left(p+q-1, 2q+1, \frac{P^* B}{m}\right)} \right\} \quad (36)$$

The local heat flux at the sheet can be expressed as

$$q_w = -k_m \frac{\partial T}{\partial y} = -k_m D x \sqrt{\frac{c\rho_f}{\mu}} \theta_1'(0) \quad (37)$$

$$\therefore \theta_1'(0) = -\left\{ m(p+q) + \left(P^* B \frac{p+q-1}{2q+1} \right) \frac{M\left(p+q-1, 2q+1, \frac{P^* B e^{-m\eta}}{m}\right)}{M\left(p+q-1, 2q+1, \frac{P^* B}{m}\right)} \right\} \quad (38)$$

Case(ii) **The Prescribed Surface Heat Flux (PHF) Case**

In the PHF case, the dimensionless temperature is assumed to be of the form,

$$T - T_\infty = \frac{Ex}{k_m} \sqrt{\frac{\mu}{c\rho_f}} h_1(\eta) \quad (39)$$

and the corresponding energy equation and boundary conditions become

$$(1+Nr) h_1'' + P\left(A - \frac{e^{-m\eta}}{m} \right) h' + P\alpha h = 0 \quad (40)$$

and

$$h_1'(0) = -1 \quad , \; h_1(\infty) \to 0 \quad (41)$$

The solution of equation is obtained as

$$h_1(\eta) = c_1 e^{-m(p+q)\eta} M\left(p+q-1, 2q+1, \frac{P^* B e^{-m\eta}}{m} \right) \quad (42)$$

Where

$$c_1 = \left[m(p+q) M\left(p+q-1, 2q+1, \frac{P^* B}{m} \right) + P^* B \left(\frac{p+q-1}{2q+1} \right) M\left(p+q, 2q+2, \frac{P^* B}{m} \right) \right]^{-1} \quad (43)$$

By equating the coefficients we get

$$(1+Nr) h_1'' + p\left(A - \frac{e^{-m\eta}}{m} \right) h_2' + p\alpha h_2 = -\frac{c_p \mu}{k_m} \frac{M_{L,P}\left(\frac{Q_1^2}{m^2 p_1} e^{-m\eta} \right)}{M_{L,P}\left(\frac{Q_1^2}{m^2 p_1} \right)} \quad (44)$$

$h_1'(0) = 0$, $h_1(\infty) \to 0$, whose solution is given by

$$\left(\frac{\frac{\Gamma(2(p+q)-1)\Gamma(2q+1)}{\Gamma(p+q+1)\Gamma(3q+p+1)}}{(p+q+1)\left(p+q+\frac{P^* A}{m} \right) + \frac{P^* \alpha}{m}} \xi \right) \xi^{p+q} \quad (45)$$

3. Asymptotic Analysis

In this section we derive the asymptotic expressions of the temperature functions $\varphi(x,\eta)$ and $h(x,\eta)$ valid for both large and small the modified Prandtl numbers.

3.1 The Prescribed Surface Temperature (PST) Case:

The Kummer's function can be approximated to the first order as

$$M\left(a,b,-z\right)\approx\left(1+c_0 z\right)^{-a} \quad (46)$$

with

$$M\left(a,b,-z\right)\approx 1 \text{ as } z\to 0 \quad (47)$$

and

$$M\left(a,b,-z\right)\approx\left(c_0 z\right)^{-a} \text{ as } z\to\infty \quad (48)$$

Where c_0 is a constant to be determined by matching equation

$$c_0=\left(\frac{\Gamma(b)}{\Gamma(b-a)}\right)^{-\frac{1}{a}} \quad (49)$$

Now,

$$M\left(p+q-1,2q+1,\frac{P^*Be^{-m\eta}}{m}\right)\sim \left(1-\frac{C_1P^*Be^{-m\eta}}{m}\right)^{1-(p+q)} \quad (50)$$

and

$$M\left(p+q-1,2q+1,\frac{P^*B}{m}\right)\sim\left(1-\frac{C_1P^*B}{m}\right)^{1-(p+q)} \quad (51)$$

where

$$C_1=\left(\frac{\Gamma(2q+1)}{\Gamma(p+q-1)}\right)^{-\frac{1}{p+q-1}} \quad (52)$$

The temperature function $\phi\left(x,\eta\right)$ can be approximated as,

$$\varphi\left(x,\eta\right)= x\left\{e^{-m(p+q)\eta}\left(\frac{1-C_1\dfrac{P^*Be^{-m\eta}}{m}}{1-C_1\dfrac{P^*B}{m}}\right)^{1-p-q}\right\} \quad (53)$$

3.2 The Prescribed Surface Heat Flux (PHF) Case:

In PHF case, the temperature function $H(x,\eta)$ valid for both large and small modified Prandtl number is given by,

$$h\left(\eta\right)=C_3e^{-m(p+q)\eta}\left(1-\frac{C_1P^*Be^{-m\eta}}{m}\right)^{1-(p+q)} \quad (54)$$

Where

$$C_3=\left(m\left(p+q\right)\left(1-\frac{C_1P^*B}{m}\right)^{1-(p+q)} +P^*B\left(\frac{p+q-1}{2q+1}\right)\left(1-\frac{C_2P^*B}{m}\right)^{-(p+q)}\right)^{-1} \quad (55)$$

$$C_2=\left(\frac{\Gamma(2q+2)}{\Gamma(q-p+2)}\right)^{-\frac{-1}{p+q}} \quad (56)$$

$$H\left(x,\eta\right)=x\left[C_3e^{-m(p+q)\eta}\left(1-C_1\frac{P^*Be^{-m\eta}}{m}\right)^{1-(p+q)}\right] \quad (57)$$

4. RESULTS AND DISCUSSION

In this paper, we consider the effect of radiation, magnetic field and temperature dependent heat source over a stretching sheet, with variable PST/PHF using Kummer's functions.

From the table the dimensionless temperature gradient at the wall $\theta_1'\left(0\right)$ increases with K, α and Nr but decreases with Λ, R and Pr which implies that the thermal boundary layer thickness will increase with Λ, R but will decrease with K, α and Nr. As Pr increases $\theta_1'(0)$ decreases. Wall temperature $h(0)$ behaves similar to $\theta_1'(0)$. Asymptotic expressions of temperature functions valid for large and small modified Prandtl numbers are presented.

Λ	K	R	α	Pr	Nr	$\theta_1'(0)$	$h(0)$
1	0	0.1	-0.2	1	0	-1.1652	0.8582
	1					-1.0882	0.9189
	2					-1.0363	0.9650
	5					-0.9417	1.0620
0.5	1	0.1	-0.2	1	0	-0.9905	1.0096
1						-1.0882	0.9189
2						-1.1703	0.8545
5						-1.2490	0.8006
1	1	0	-0.2	1	0	-1.0351	0.9661
		0.1				-1.0882	0.9189
		0.5				-1.3252	0.7541
		1.0				-1.6690	0.5991
1	1	0.1	-0.2	1		-1.0882	0.9189
			0		0	-0.9489	1.0538
			0.2			-0.8523	1.1733
1	1	0.1	-0.2	0.5	0	-0.6900	1.4492
				1		-1.0882	0.9189
				2		-1.6885	0.5922
				5		-2.9569	0.3382
1	1	0.1	-0.2	1	0	-1.0882	0.9189
					1	-0.6900	1.4492
					2	-0.5256	1.9022
					5	-0.3291	3.0380

5. CONCLUSIONS

Here we have studied the flow and heat transfer of a magnetohydrodynamic viscous fluid-saturated porous medium, past a permeable and non-isothermal stretching sheet with internal heat generation or absorption and radiation. Closed-form solutions to the full Darcy-Brinkman equations, without applying to boundary layer approximations, are found using a similarity transformation. The temperature functions for two heating conditions are given in terms of Kummer's functions. Asymptotic expressions of the temperature functions are also presented valid for both large and small modified Prandtl numbers.

The exact solutions to the flow and heat transfer problems for a viscous fluid saturated porous medium over a permeable non-isothermal stretching sheet in the presence of magnetic field without using boundary layer theory are presented here. We find that the temperature function decreases with increasing viscosity ratio, porous parameter and suction parameter keeping all other parameters fixed.

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