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RADIATION EFFECT ON TRANSIENT FREE CONVECTIVE MHD HEAT TRANSFER FLOW THROUGH POROUS MEDIUM

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Abstract

This paper analytically investigates the one-dimensional unsteady laminar magnetohydro-dynamic (MHD) boundary layer flow of a viscous, incompressible fluid past an exponentially accelerated, infinite vertical plate. The effects of a transverse magnetic field, thermal radiation, and flow through a porous medium are considered, with both the plate and the medium assumed to be porous. The fluid is treated as optically thin, and the magnetic Reynolds number is assumed small enough to neglect induced magnetic fields. The governing boundary layer equations are nondimensionalized and solved using a perturbation method. Analytical expressions for transient velocity, temperature, skin friction, and Nusselt number are obtained and graphically analyzed for various physical parameters.

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Intr**oduction**

In recent years, convective heat transfer in porous media has garnered significant attention due to its broad industrial and technological applications, including geothermal energy recovery, oil and gas extraction, thermal insulation using fibrous and granular materials, electronic system cooling, and the development of regenerative heat exchangers. The unique properties of porous media— such as high surface area, complex internal structures, and variable permeability—strongly influence heat and mass transfer processes. Consequently, a thorough understanding of convective heat transfer in these systems is crucial for improving performance and efficiency across various engineering fields [1-14].

The influence of radiation on magnetohydrodynamic (MHD) flow and heat transfer has become increasingly significant in industrial applications, particularly at high operating temperatures where radiative heat transfer cannot be neglected. In engineering systems such as nuclear reactors, gas turbines, and propulsion units for aircraft, missiles, satellites, and space vehicles, effective thermal management is essential. Accurate modeling of radiation effects is critical to achieving optimal design and performance. At elevated temperatures, thermal radiation contributes substantially to overall heat transfer, necessitating its inclusion in predictive models. Consequently, extensive research has focused on transiente- free convective MHD flows, with special emphasis on the role of radiative heat transfer in shaping the fluid dynamics and thermal behavior of such systems [15-32].

There is a substantial interest of the recent researchers in the flows of non-Newtonian fluids. Such motivation in these fluids is mainly because of their use in the industrial and technological applications. Many materials like mud, pasta, personal care products, ice cream, paints, oils, cheese, asphalt etc. are non-Newtonian fluids. Most biological fluids with higher molecular weight components are also non-Newtonian in nature. The usual properties of polymer melts and solutions together with the desirable attributes of many polymeric solids, have given rise to the world-wide industry of polymer processing. The non-Newtonian fluids in particular have key importance in geophysics, chemical and nuclear industries, material processing, oil reservoir engineering, bioengineering and many others. Rheological properties of all the non-Newtonian fluids cannot be predicted using single constitutive equation (unlike the case of viscous fluids). Therefore many models of non-Newtonian fluids are based either on "natural" modifications of established macroscopic theories or molecular considerations. The additional rheological parameters in the constitutive equations of non-Newtonian fluids are the main culprit for the lack of analytical solutions. The resulting equations are more complex and higher order than the Navier-Stokes equations [33-43].

The objective of this study is to derive an analytical solution for the one-dimensional, unsteady, laminar boundary layer flow of a viscous, incompressible fluid past an infinitely long vertical plate that is exponentially accelerated. The analysis considers the influences of the following physical effects:

- Transverse magnetic field (representing the MHD aspect),
- Thermal radiation (affecting energy transport),
- Porous medium (affecting momentum and heat transfer resistance).

Formulation of the Problem

An unsteady one – dimensional laminar free convection flow of a viscous incompressible fluid past an infinite vertical porous plate through a porous medium with variable temperature is considered. The x - axis is being taken vertically upwards along the vertical plate and y - axis to be normal to the plate. The physical model and coordinate system of the flow problem is shown in figure (1).

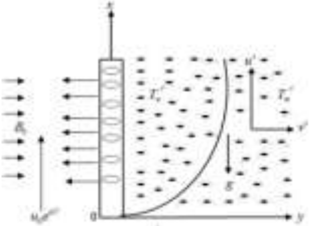

Figure (1): Physical model and coordinate system

Initially, it is assumed that the plate and fluid are at the same temperature T_∞ in the stationary condition. At $t' \geq 0$, the plate is exponentially accelerated with a velocity $u' = u_0{}' \exp\left(a't'\right)$ in its own plane and the plate temperature is raised linearly with time t. A uniform magnetic field is applied in the direction perpendicular to the plate. The fluid is assumed to be slightly conducting, so that the magmatic Reynolds number is much less than unity and hence the induced magnetic field is negligible in comparison with the applied magnetic field. The fluid considered here is a gray, absorbing/emitting radiation but a non scattering medium. The viscous dissipation is also assumed to be negligible in the energy equation as the motion is due to free convection only. It is also assumed that all the fluid properties are constant except for the density in the buoyancy term, which is given by the usual Boussinesq's approximation. Under these assumptions the governing boundary layer equations are

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu'\frac{\partial^2 u'}{\partial y'^2} + g\beta\left(T' - T'_\infty\right) - \frac{\sigma B_0^2}{\rho}u' - \nu\frac{u'}{k'} \tag{1}$$

$$\rho C_p\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = \kappa\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} \tag{2}$$

with the following initial and boundary conditions:

$$\begin{aligned}
&u' = 0, \quad T' = T'_\infty && \forall \quad y', \quad t' \leq 0\\
&u' = u_0\exp\left(a't'\right), T' = T'_\infty\left(T'_w - T'_\infty\right)At' && at\ \ y' = 0\\
&u \to 0, \quad T \to T'_\infty && as\ \ y \to \infty
\end{aligned} \tag{3}$$

where $A = \dfrac{u_0^1}{\nu}$

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^*\sigma\left(T'^4_\infty - T'^4\right) \tag{4}$$

We assume that the temperature differences within the flow are sufficiently small such that T'^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T'^4 in a Taylor series about T'^4_∞ and neglecting higher order terms; thus

$$T'^4 = -4T'^3_\infty\left(T' - 3T'^4_\infty\right) \tag{5}$$

By using equation (4) and (5), equation (2) gives

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa \frac{\partial^2 T'}{\partial y'^2} - 16 a^* \sigma T_\infty'^3 \left(T_\infty' - T' \right) \tag{6}$$

In order to write the governing equations, initial and the boundary conditions the following non-dimensional quantities are introduced.

$$\begin{gathered} Y = \frac{y' v_o}{\nu},\ U = \frac{u'}{u_w},\ t = \frac{t' u_0}{\nu},\ T = \frac{T' - T_\infty'}{T_w{}' - T_\infty'},\ Gr = \frac{g \beta \nu \left(T_w{}' - T_\infty' \right)}{u_0^3} \\ M = \frac{\sigma B_0^2 \nu}{\rho}, k = \frac{k' u_0^2}{\nu^2}, R = \frac{16 a^* \sigma T_\infty'^3}{\kappa u_0^2}, a = \frac{a' \nu}{u_0^2}, \gamma = -\frac{\nu'}{u_0}, \Pr = \frac{\mu C_p}{k} \end{gathered} \tag{7}$$

In view of (7) the equations (1) and (6) are reduced to the following non-dimensional form

$$\frac{\partial U}{\partial t} - \gamma \frac{\partial U}{\partial Y} = \frac{\partial^2 U}{\partial Y^2} + Gr\, T - M\, U - \frac{1}{k} U \tag{8}$$

$$\frac{\partial T}{\partial t} - \gamma \frac{\partial T}{\partial Y} = \frac{1}{\Pr} \frac{\partial^2 T}{\partial Y^2} - \frac{R}{\Pr} T \tag{9}$$

with following initial and boundary conditions:

$$\begin{array}{lll} U = 0, \quad T = 0 & \forall \quad Y, \quad t' \le 0 & \\ U = \exp(at), T = t & t > 0, at\ Y = 0 & \\ U \to 0, \quad T \to 0 & as\ \ Y \to \infty & \end{array} \tag{10}$$

where Gr is the thermal Grashof number, $\Pr$ is the fluid Prandtl number, R is the radiation parameter, M is the magnetic parameter, a' is the accelerating parameter, a dimensionless accelerating parameter, a^* absorption coefficient, c_p specific heat at constant pressure, B_0 transverse magnetic field strength, g acceleration due to gravity, κ thermal conductivity of the fluid, k' permeability parameter, k dimensionless permeability parameter, q_r radiative heat flux in the $y-$direction, t' time, t dimensionless time, T' temperature, T dimensionless temperature, T_w' is the temperature of the plate, T_∞' is the temperature of the fluid far away from the plate, u' is the $x-$component of the velocity, u_0' velocity of the plate, U is the dimensionless velocity, V' is the $y-$component of velocity, y' is the coordinate axis normal to the plate, Y is the dimensionless coordinate axis normal to the plate, β is the volumetric coefficient of thermal expansion, γ is the suction parameter, ν is the kinematic viscosity, ρ is the fluid density, σ is the electrical conductivity of fluid.

Method of Solution

Equation (8) - (9) are coupled, non – linear partial differential equations and these cannot be solved in closed – form using the initial and boundary conditions (10). However, these equations can be reduced to a set of ordinary differential equations, which can be solved analytically. This can be done by representing the velocity, temperature and concentration of the fluid in the neighbourhood of the fluid in the neighbourhood of the plate as

$$\begin{aligned} U(y,t) &= U_0(y) + U_1(y)e^{at} \\ T(y,t) &= T_0(y) + T_1(y)e^{at} \end{aligned} \tag{11}$$

Substitute equation (11) in to the equations (8) and (9) the set of ordinary differential equations are the following form

$$U_0'' + \gamma U_0' - \beta_3 U_0 = -Gr\,T_0 \tag{12}$$

$$U_1'' - \beta_4 U_1 = -Gr\,T_1 \tag{13}$$

$$T_0'' + \beta_1 T_0' - R\,T_0 = 0 \tag{14}$$

$$T_1'' - \beta_2 T_1 = 0 \tag{15}$$

The exact solution for the fluid velocity $U(y,t)$, fluid temperature $\theta(y,t)$ are obtained and expressed from equations from (12) - (15) in the following form:

$$U(y,t) = K_1 e^{m2y} + K_2 e^{m4y}$$

$$T(y,t) = t\,e^{m2y}$$

Skin friction

$$\tau = \left(\frac{\partial U}{\partial y}\right)_{y=0} = m_2 K_1 + m_4 K_2$$

Nusselt number

$$Nu = \left(\frac{\partial T}{\partial y} \right)_{y=0} = t\, m_2$$

Appendix

$$m_2 = -\left(\frac{\gamma \Pr + \sqrt{\gamma^2 \Pr^2 + 4R}}{2} \right), m_4 = -\left(\frac{\gamma + \sqrt{\gamma^2 + 4\beta_3}}{2} \right), K_1 = -\left(\frac{Grt}{m_2^2 + \gamma m_2 - \beta_3} \right)$$

$$K_2 = \left(e^{at} - K_1 \right), \beta_1 = \gamma \Pr, \beta_2 = \left(R - \Pr + \Pr at \right), \beta_3 = \left(M + \frac{1}{k} \right), \beta_4 = \left(\beta_3 + at - \gamma \right)$$

Results and Discussion

In order to better understand the physical characteristics of the problem, numerical simulations have been conducted to evaluate the velocity profiles, temperature distribution, skin friction coefficient, and Nusselt number for a range of parameter values of magnetic field parameter (M), Grashof number (Gr), accelerating parameter (a), suction parameter (γ), permeability parameter (K), radiation parameter(R) and time $(t)$are presented graphically in figures (2) – (13). The transient velocity profiles for different values of Grashof number $(Gr)$are shown in figure (2). The Grashof number signifies the relative effect of the buoyancy force to the hydrodynamic viscous force. The positive values of Grashof number correspond to cooling of the plate and the negative values of Grashof number correspond to heating of the plate by free convection. As expected, it is found that an increase in the Grashof number lead to increase in the velocity due to enhancement in the buoyancy force. The transient velocity profiles for different values of magnetic parameter(M) are depicted in figure (3). It is observed form this figure that an increase in magnetic field leads to decrease in the velocity profiles for both the cases of cooling $(Gr = 2)$and heating $(Gr = -2)$of the porous plate. It is because that the application of transverse magnetic field will result a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. The effects of suction parameter on velocity profiles illustrated in figure (4), it is found here that velocity decreases with increase of the suction parameter for both cases of cooling $(Gr = 2)$and heating $(Gr = -2)$of the porous plate. The effect of permeability parameter (K) and time (t)on velocity profiles are depicted in figure (5). It can be seen that the velocity increases with increase of permeability parameter and time. The transient velocity profiles for different values of the accelerating parameter and the radiation parameter are presented in figure (6). It is observed that the velocity decreases with an increase in the radiation parameter, whereas it increases with an increase in the accelerating parameter. Figure (7) displays the velocity profiles for different values of Prandtl number (Pr), it is clear that the velocity decreases with increasing values of Prandtl number. Effects of radiation parameter (R), suction parameter (a), Prandtl number (Pr) and time (t) on temperature profiles are shown in figure (8), (9), (10) and (11) respectively. It is observed form these figures that temperature decrease with increased values of radiation parameter, suction parameter and Prandtl number, but increases with increased values of time. Figure (12) shows the variation of the Nusselt number for different values of the suction parameter. It is observed that the rate of heat transfer decreases as the suction parameter increases. Figure (13) depicts the influence of the Grashof number on skin friction. It is evident from the figure that, for the case of cooling of the porous plate, an increase in the Grashof number leads to an increase in skin friction. This trend can be attributed to the enhancement of buoyancy forces which augment

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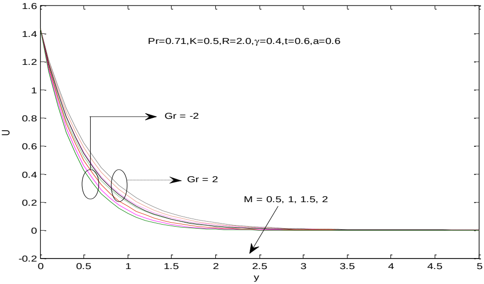

Figure (3): Veloicty profiles for different values of M

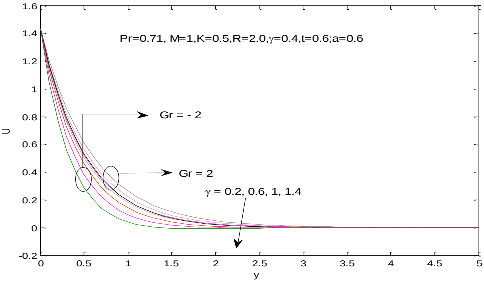

Figure (4): Veloicty profiles for different values of γ

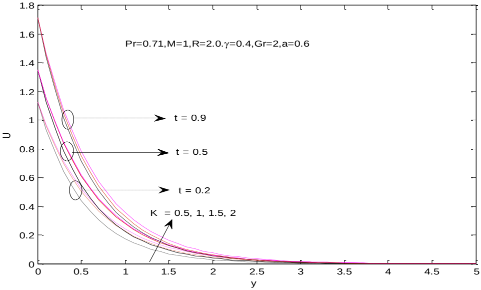

Figure (5): Veloicty profiles for different values of K

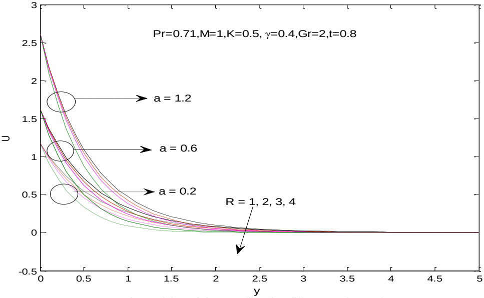

Figure (6): Veloicty profiles for different values of R

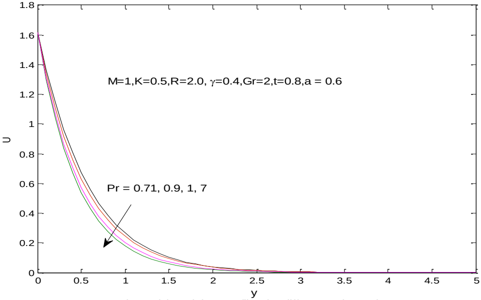

Figure (7): Veloicty profiles for different values of Pr

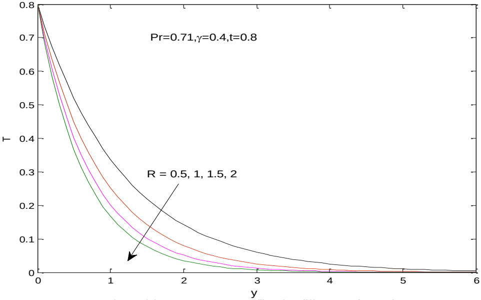

Figure (8): Temperature profiles for different values of R

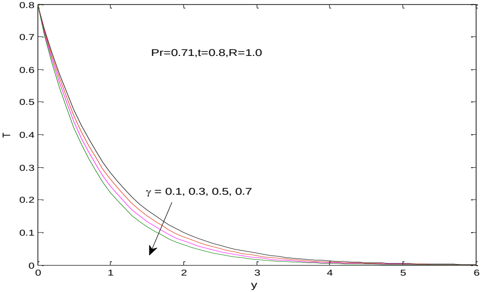

Figure (9): Temperature profiles for different values of γ

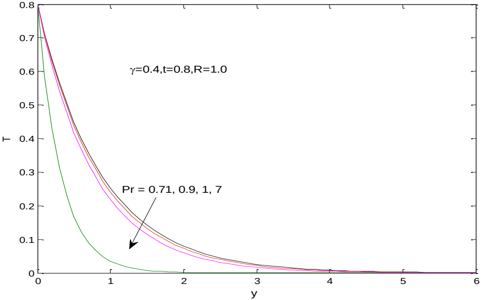

Figure (10): Temperature profiles for different values of Pr

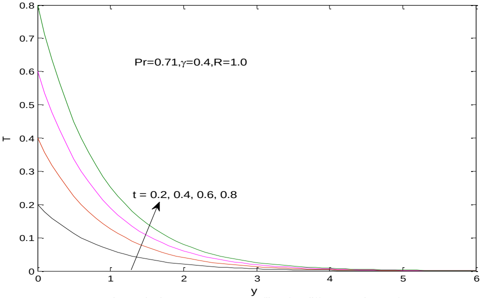

Figure (11): Temperature profiles for different values of t

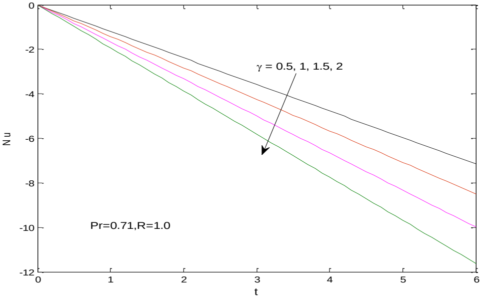

Figure (12): Nusselt number for different values of R

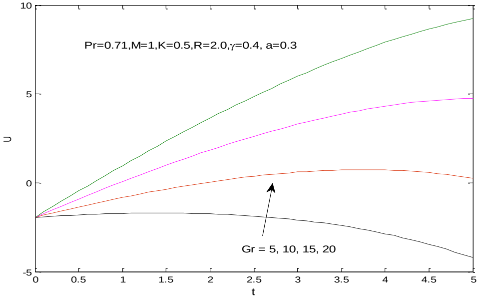

Figure (13): Skin friction for different values of Gr