IX International Conference on Computational Heat and Mass Transfer, ICCHMT 2016

Heat transfer in MHD mixed convection viscoelastic fluid flow over a stretching sheet embedded in a porous medium with viscous dissipation and non-uniform heat source/sink

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Abstract

A numerical model is developed to study the MHD mixed convective boundary layer viscoelastic fluid flow over a stretching sheet embedded in a porous medium in presence of viscous dissipation and non-uniform heat source have been investigated. The governing partial differential equations are converted into ordinary differential equations by applying suitable similarity transformations. The numerical solution of the problem is also obtained by the efficient Runge-Kutta-Fehlberg method with shooting technique. Here two types of different heating processes are considered namely, PST and PHF cases. The effect of various physical parameters such as Prandtl number, Eckert number, magnetic parameter, convection parameter and porous parameter which determine the temperature profiles are shown in several plots. Some important findings reported in this work reveals that the effect of viscous dissipation and non uniform heat source have significant impact in controlling the rate of heat transfer in the boundary layer region.

Keywords: Heat transfer; stretching sheet; viscoelastic liquid; non-uniform heat source; Prandtl number;

1. Introduction

Investigation on boundary layer behavior of a viscoelastic fluid over a continuously stretching surface finds many important applications in engineering processes. Some of these applications include polymer extrusion, drawing of plastic films and wires, glass fiber and paper production, crystal growing, liquid films in condensation process, etc. The ever increasing applications in these industrial processes have led to a renewed interest in the study of viscoelastic fluid flow and heat transfer over a stretching sheet. In recent years a great deal of work has been carried out to reveal the flow, heat and mass transfer in viscoelastic fluid flow past a stretching surface. Rajagopal et al. [1] have considered the study of visco-elastic second order fluid flow over a stretching sheet by solving boundary layer equations numerically; this work does not take into account of the heat transfer phenomenon. Bujurke et al. [2] have presented work to analyse momentum and heat transfer phenomena in visco-elastic second order fluid over a stretching sheet with internal heat generation and viscous dissipation. An exact analytical solution of MHD flow of a viscoelastic liquid of past stretching sheet has been presented by Andersson [3]. Khan [8] and Bataller [9] investigated the effect of thermal radiation on heat transfer in a boundary layer viscoelastic second-order fluid flow over a stretching sheet with internal heat source/sink. Nagraja et al. [4] have presented the coefficients of skin-friction and heat transfer obtained from the closed-form solutions for the boundary layer equations of the flow of viscoelastic fluid over a stretching surface having power-law temperature. Vajravelu [5] studied flow and heat transfer in a viscous fluid over a non-linearly stretching sheet

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without viscous dissipation, but the heat transfer in this flow is analyzed in the only case when the sheet is held at a constant
temperature.

The present author also explored the MHD free convection effect on the heat transfer in a porous medium. Several analyses have
been carried out to investigate the MHD boundary layer flow and heat transfer characteristics of a viscoelastic fluid past a stretching
surface. In the analysis of Datti et al. [6] the effects of thermal radiation and temperature-dependent thermal conductivity on MHD
visco-elastic flow have been examined. Khan and Sanjayanand [7] presented approximate analytical solution of the viscoelastic
boundary layer flow and heat transfer over an exponential stretching continuous sheet. They considered the influence of viscous
dissipation on thermal transport and concluded that significant increase of Eckert number might reverse the direction of heat
transfer to the stretching sheet.

Another effect which bears great importance on heat transfer is the viscous dissipation. The determination of the temperature
distribution when the internal friction is not negligible is of utmost significance in different industrial fields, such as chemical and
food processing, oil exploitation and bio-engineering. In view of this, viscoelastic flow and heat transfer over a flat plate with
constant suction, thermal radiation, and without viscous dissipation were studied by Salem [10] used a shooting technique to study
numerically the effects of variable viscosity and thermal conductivity on the MHD flow and heat transfer of a viscoelastic fluid over
a stretching surface with variable surface temperature. The flow is induced due to an infinite elastic sheet which is stretched back
and forth in its own plane. Temperature field and wall temperature gradient are obtained. The combined effects of Joule heating and
viscous dissipation on the momentum and thermal transport have been examined by Chen [11] Effects of free convection, thermal
radiation, and surface suction/blowing on the flow and heat transfer characteristics are also examined. Uddin et al. [12] investigated
the effects of mass transfer on MHD mixed convective flow along inclined porous plate. R. Ravidran et al. [13] studied the effect of
non-uniform single and double slot suction/injection into an unsteady mixed convection flow of an electrically conducting and heat
generating/absorbing fluid over a vertical cone in the presence of magnetic field and a first order chemical reaction. Yahaya et al.
[14] presented a unified approach to solving the MHD flow due to influence of buoyancy and thermal radiation over a stretching
porous sheet using homotopy analysis method. N. Sandeep et al. [15] investigated the influence of non-uniform heat source/sink,
mass transfer and chemical reaction on an unsteady mixed convection boundary layer flow of a MHD micropolar fluid past a
stretching sheet in presence of viscous dissipation and suction/injection, most recently.

The aim of present works we contemplate to study the effect of viscous dissipation and non-uniform heat source/sink on MHD
mixed convective viscoelastic flow and heat transfer over a permeable stretching sheet. We studied the heat transfer characteristics;
two different types of boundary conditions are considered, namely, PST and PHF boundary conditions.

2. Mathematical formulation

Consider a steady laminar two-dimensional flow of an incompressible electrically conducting Visco-elastic fluid past a porous
stretching sheet. The flow is generated due to stretching sheet along \( x \)-axis by application of two equal and opposite forces. The
sheet is stretched with the speed varying linearly with the distance from the slit, we take \( x \)-axis along the surface, \( y \)-axis being
normal to it and \( u \) and \( v \) are the fluid tangential velocity and normal velocity respectively.

With these assumptions the flow-governing equations are given by,

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\nu}{k'} \left[ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\nu}{\rho} \frac{\partial^2 u}{\partial y^2} \right] + \frac{\alpha B_0^2}{\rho} u
\]

where \( u \) and \( v \) velocity components along \( x \) and \( y \) directions, \( \nu \) kinematic viscosity, \( k' \) permeability of the porous medium,
\( \rho \) is the density, \( B_0 \) is the strength of applied magnetic field, \( \alpha \) is the electrical conductivity of the fluid. \( k_0 \) is the first
moment of the distribution function of relaxation times.

The boundary conditions are

\[
u = bx, v = 0, \text{ at } y = 0 \text{ and } u \to 0, \text{ as } y \to \infty
\]

Eqs. (1) and (2), subjected to boundary condition (3), admit self-similar solution in terms of the similarity function \( f \) and the
similarity variable \( \eta \) defined by

\[
u = bx f^4(\eta), v = -\sqrt{\nu} f^2(\eta), \eta = \frac{b}{v} y.
\]
Substituting these in Eq.(2) we obtain the following ordinary differential equation:

\[ f'''' - f''' + f'' - k_1 f' \cdot k_2 \left[ 2f f''' - f f'' - f' \right] + Gr \theta - Mn f'' = 0 \]  

(5)

where "I" denotes the differentiation with respect to \( \eta \), \( k_1 = k_2 / \nu \) is the visco-elastic parameter, \( Mn = \sigma B_0^2 / \rho b \) is magnetic parameter, \( k_2 = \nu / \nu b \) porous parameter and \( Gr = Gb(T - T_s) / b^2 x \) is convection parameter.

In deriving the above equation it is assumed that the induced magnetic field is negligibly small and the cooling liquid has weak electrical conductivity so that any charge generated during the process gets accumulated on the extrusion and moreover the dynamics of the liquid around the sheet is not so strong, hence this issue requires least attention.

The boundary conditions (3) in terms of \( f \) are:

\[ f(\eta) = 0, f'(\eta) = 1 \text{ at } \eta = 0 \text{ and } f'(\eta) \to 0 \text{ as } \eta \to \infty \]  

(6)

3. Heat Transfer Analysis

The governing boundary layer heat transport equation in the presence of non-uniform heat source, viscous dissipation and magnetic field is given by,

\[
\frac{\partial T}{\partial x} + \frac{\rho c_p}{\partial y} = \frac{k}{\rho c_v} \left( \frac{\partial u}{\partial x} \right)^2 + \frac{q'''}{\rho c_v} + \frac{\sigma B_0^2 u'}{\rho c_v},
\]  

(7)

where \( k \) is the thermal conductivity, \( \rho \) is the density of the fluid, \( c_p \) is the specific heat at constant pressure, \( \mu \) is the viscosity, and \( q'' \) is the non-uniform heat source.

\[
q''' = \left( \frac{ku}{\rho c_v} \right) A'(T_w - T_s) + B'(T - T_s)
\]  

(8)

where \( A' \) and \( B' \) are coefficients of space and temperature dependent heat source/sink respectively. Here we make a note that the case \( A' > 0 \) and \( B' > 0 \) correspond to internal heat generation and that \( A' < 0 \) and \( B' < 0 \) correspond to internal heat absorption.

3.1. Prescribed Surface Temperature (PST)

For this heating process, the prescribed surface temperature is assumed to be a quadratic function of \( x \) and is given by,

\[
T = T_w = T_s + A \left( \frac{x}{l} \right)^2 \text{ at } y = 0 \text{ and } T \to T_s \text{ as } y \to \infty,
\]  

(9)

where \( A \) is constant, \( l = \sqrt{\nu / b} \) is a characteristic length, \( T \) fluid temperature of the moving sheet, \( T_w \) is the wall temperature and \( T_s \) is the temperature of the fluid away from sheet.

Now we define the non-dimensional temperature \( \theta(\eta) \) as

\[
\theta(\eta) = \frac{T - T_s}{T_w - T_s}.
\]  

(10)

Where \( T - T_s = A(x/l)^2 \theta(\eta) \) and \( T_w - T_s = A(x/l)^2 \). Eq.(10) in Eqs.(7) we obtain the following non-linear ordinary differential equation for \( \theta(\eta) \)

\[ \theta'' - 2Pr f' \theta + Pr f \theta' + Ecf \theta'' + [A' f' + B' \theta] + Mn Pr Ecf = 0 \]  

(11)
The non-dimensionnal parameter \(\Pr\), \(Ec\), \(Mn\) in the above equation, denote Prandtl number, Eckert number and magnetic parameter respectively and are defined as follows:

\[
\Pr = \frac{\mu c_p}{k}, \quad Ec = b^2 l^2 / A c_p, \quad Mn = \sigma B_0^2 / \rho.
\]

Corresponding boundary conditions become

\[
\theta(\eta) = 1 \quad \text{at} \quad \eta = 0, \quad \text{and} \quad \theta(\eta) \rightarrow 0 \quad \text{as} \quad \eta \rightarrow \infty
\]  

(12)

The solution of the heat transport Eq.(11), subjected to boundary conditions of Eq.(12) can be obtained analytically by power series method in terms of Kummer’s function of hypergeometric series as:

\[
\theta(\eta) = c_1 e^{-a \frac{\eta}{2}} M \left( \frac{a+b}{2} - \frac{2,1+b,-\frac{\Pr}{\alpha^2} e^{-a\eta}}{e^{-a\eta}} \right) + c_2 e^{-a\eta} + c_3 e^{-2a\eta}
\]

(13)

\[
c_1 = \left[ \frac{1-(c_2-c_3)}{M \frac{a+b}{2} - \frac{2,1+b,-\frac{\Pr}{\alpha^2}}{e^{-a\eta}}} \right], \quad c_2 = \left[ \frac{-A^*}{4a^2 - 2\Pr + B^*} \right], \quad c_3 = \left[ \frac{-Ec\alpha^4 + Mn\alpha^2}{4a^2 - 2\Pr + B^*} \right], \quad a = \frac{\Pr}{\alpha^2}, \quad b = \sqrt{a^2 - 4B^*/a^2}
\]

(14)

the wall temperature gradient and the local heat flux are given by, respectively

\[
\theta'(0) = c_1 \left[ -a \left( \frac{a+b}{2} \right) M \left( \frac{a+b-4}{2} - \frac{\Pr}{\alpha^2} \right) + \left( \frac{a+b-4}{2+2b} \right) \left( \frac{\Pr}{\alpha} \right) M \left( \frac{a+b-2}{2} - \frac{\Pr}{\alpha^2} \right) \right] - \alpha c_2 - 2\alpha c_3
\]

(15)

\[
q_w = -k \left( \frac{\partial T}{\partial y} \right) _w = -k \sqrt{\frac{D}{\rho}} (T_w - T_\infty) \theta'(0)
\]

(16)

3.2. Prescribed heat flux (PHF)

The boundary conditions in case of power law heat flux in the form,

\[
-k \frac{\partial T}{\partial y} = q_w = D \left( \frac{x}{l} \right)^2 \text{at} \quad y = 0 \quad \text{and} \quad T \rightarrow T_\infty \quad \text{as} \quad y \rightarrow \infty
\]

(17)

where \(D\) is a constant, \(k\) is the thermal conductivity, \(q_w\) local heat flux and \(l\) is a characteristic length.

Now we define a non-dimensional temperature \(g(\eta)\) as,

\[
g(\eta) = \frac{T - T_w}{T_w - T_\infty}
\]

(18)

\[
T_w - T_\infty = \frac{D}{k} \left( \frac{x}{l} \right)^2 \sqrt{\frac{l}{T \rho \beta}} \quad \text{and} \quad T - T_\infty = \frac{D}{k} \left( \frac{x}{l} \right)^2 \sqrt{\frac{l}{T \rho \beta} g(\eta)}
\]

(19)

using Eqs.(17) and (18) in Eq.(7) we obtain the non-linear ordinary differential equation for \(g(\eta)\) in the form

\[
g'' - 2\Pr f' g + \Pr f' g' + Ec f'' + [A^* f' + B^* g] + Mn Ec f' = 0
\]

(20)
Here "I" denotes the differentiation with respect to th similarity variable $\eta$ and all other parameters are in analogy with that of PST case but differ only by constant D i.e., the definition involving the constant A in PST must be replaced by D in PHF.

Corresponding boundary conditions for $g(\eta)$ are given by

$$g'(\eta) = -1 \text{ at } \eta = 0 \text{ and } g(\eta) \to 0 \text{ as } \eta \to \infty \quad (21)$$

The solution of (20), subject to the boundary conditions (21) can be obtained by power series method in terms of hypergeometric Kummer’s function as:

$$g(\eta) = c_4 e^{-\left(\frac{a+b}{2}\right)\eta} M\left(\frac{a+b}{2}, 1, 1; -\frac{\Pr}{\alpha^2} e^{-a\eta}\right) + c_2 e^{-a\eta} + c_3 e^{-2a\eta} \quad (22)$$

Where, $c_4 = \frac{a(c+2c_t)-1}{\left(-a\right)^{\frac{a+b}{2}} M\left(\frac{a+b}{2}, 1; -\frac{\Pr}{\alpha^2}\right) + \left[\frac{\Pr}{\alpha}\right] \left(\frac{a+b-2}{2} + b; -\frac{\Pr}{\alpha}\right)}$ \quad (23)

The non-dimensional wall temperature derived from Eq. (22) reads as:

$$g(0) = c_4 e^{-\left(\frac{a+b}{2}\right)\eta} M\left(\frac{a+b-4}{2}, 1; -\frac{\Pr}{\alpha^2} e^{-a\eta}\right) + c_2 e^{-a\eta} + c_3 e^{-2a\eta} \quad (24)$$

4. Numerical Solution

We adopt the shooting method with Runge-kutta-Fehlberg scheme to solve the initial value problems in PST and PHF cases mentioned in the previous section. The coupled non-linear equations (5) and (11) with boundary conditions (6) and (12) in PST case are transformed into a system of first order ordinary differential equations as follows

$$\frac{dy_1}{d\eta} = y_2, \quad \frac{dy_2}{d\eta} = y_3, \quad \frac{dy_3}{d\eta} = y_4, \quad \frac{dy_4}{d\eta} = y_5 - k_1[y_5 y_1 - k_2 y_2],$$

$$\frac{dy_5}{d\eta} = y_6, \quad \frac{dy_6}{d\eta} = \Pr[2y_2 y_3 - y_1 y_6 - MnEy_2^2] - Ecy_3^2 - A^* y_2 - B^* y_5. \quad (25)$$

The corresponding boundary conditions are

$$y_1(0) = 0, y_2(0) = 1, \quad y_3(0) = 1, \quad y_4(\infty) = 0, y_5(\infty) = 0, \quad (26)$$

Here, $y_1 = f(\eta)$ and $y_2 = \theta(\eta)$.

Aforementioned boundary value problem is converted into an initial value problem by choosing the values of $y_4(0)$ and $y_5(0)$ appropriately. Resulting initial value problem is integrated using Runge-Kutta-Fehlberg method is used to correct the guess values of $y_4(0)$ and $y_5(0)$.

Selection of an appropriate finite value of $\eta_\infty$ is the most important aspect in this method. To select $\eta_\infty$, we begin with some initial guess value and solve the problem with some particular set of parameters to obtain $\theta(0)$ ($\theta = \theta'(0)$ in PST case and $\theta = g(0)$ in PHF case). The solution process repeated with another larger (or smaller, as the case may be) value of $\eta_\infty$. The
values of $\theta(0)$ compared to their respective previous values, if they agreed to about six significant digits, the last values of $\eta_*$ is used as the appropriate value of infinity for that particular set of parameter; otherwise the procedure is repeated until further changes in $\eta_*$ which do not lead to further changes in the values of $\theta(0)$. The step length $h=0.01$ is employed for the computation purpose. The convergence criterion largely depends on fairly depends on fairly good guesses of the initial conditions in the shooting technique, and is based on the relative difference between the current and the previous iterations used, when the difference reaches $10^{-6}$ the solution is assumed to have converged and the iterative process is terminated. Then we integrate the resultant ordinary differential equations using standard fourth order Runge-Kutta-Fehlberg method with the given set of parameters.

5. Results and Discussions

In this work we analyzed MHD mixed convective flow and heat transfer characteristics of viscoelastic fluid over a stretching sheet in a porous medium is investigated, in presence of viscous dissipation and non-uniform heat source/sink. Both analytical and numerical solutions are presented highly non-linear thermal boundary layer equations. The solutions possess excellent agreement with each other. Closed form expressions are obtained for non-dimensional temperature profiles and local heat flux in terms of confluent hypergeometric function under two general cases of non-isothermal boundary conditions, namely PST and PHF cases. The boundary layer equations of momentum and heat transfer are solved analytically. The temperature profile $\theta(\eta)$ in prescribed surface temperature (PST) case and $g(\eta)$ in prescribed heat flux (PHF) case are depicted graphically. Effects of various physical parameters such as, magnetic parameter $Mn$, Prandtl number $Pr$, Eckert number $Ec$, convection parameter $Gr$ and porous parameter $K2$ are shown graphically from Figs. 1-5.

Figure 1 (a) and (b) depict the temperature profiles for PST and PHF cases respectively, for different values of $Pr$. We infer from the figures that temperature decreases with increase in $Pr$ which implies that viscous boundary layer is thinner than the thermal boundary layer.

Figure 2 (a) and (b), shows the effect of convection parameter $Gr$ on temperature distribution, in PST and PHF cases respectively. It is noticed that the temperature distribution is decreases with increase in the Grashoff number. $Gr > 0$ means heating of the fluid or cooling of the boundary surface, and $Gr = 0$ corresponds to the absence of free convection current.

The effect of porous parameter $K1$ on temperature distribution, in PST and PHF case respectively, is shown in Figure 3(a) and (b). It is observed that the effect of temperature distribution decreases with increase in the porous parameter in the boundary layer. This leads to the enhanced deceleration of the flow and hence temperature decreases in both PST and PHF cases.

Figure 4(a) and (b) demonstrates the effect of Eckert number $Ec$ in case of PST and PHF respectively. It is evident that thermal boundary layer is broadened due to increase in $Ec$, the energy dissipation exhibits an appreciable increase in the wall temperature in both PST and PHF cases. This is quite consistent with the physical situation as the dissipative energy due to elastic deformation work, frictional and ohmic heating are considered, which results increase in the thermal boundary layer.

The effect of transverse magnetic field on heat transfer is depicted in Fig 5(a) and (b), in case of PST and PHF case respectively. It is observed that the magnetic field contributes to the thickening of thermal boundary layer. The Lorentz force has the tendency to increase the temperature, the resistance offered to the flow is responsible in enhancing the temperature.

![Figure 1](image1.png)

![Figure 2](image2.png)

![Figure 3](image3.png)

![Figure 4](image4.png)

![Figure 5](image5.png)

Fig. 1 (a) PST case (b) PHF case temperature profile of prandtl number, $Gr=1.0$, $A^*=B^*=0.1$, $K1=Ec=0.2$, $Mn=1.0$, $K2=0.5$
Fig. 2 (a) PST case (b) PHF case temperature profile of convection parameter, \( Pr=1.0, A^*=B^*=0.1, K_1=E_c=0.2, M_n=1.0, K_2=0.5 \)

Fig. 3. (a) PST case (b) PHF case temperature profile of porous parameter, \( Pr=Gr=1.0, A^*=B^*=0.1, K_1=E_c=0.2, M_n=1.0. \)

Fig. 4 (a) PST case (b) PHF case temperature profile of viscous dissipation, \( Pr=Gr=1.0, B^*=A^*=0.1, K_1=0.2, M_n=1.0, K_2=0.5 \)

Fig. 5(a) PST case (b) PHF case temperature profile of magnetic parameter \( Pr=Gr=1.0, B^*=A^*=0.1, E_c=K_1=0.2, K_2=0.5 \)
6. Conclusion

In this paper an analysis has been carried out to study of MHD mixed convective flow and heat transfer in viscoelastic fluid over a stretching sheet is investigated. The several closed form solutions for the flow and heat transfer parameter in two cases thermal boundary conditions, that is prescribed surface temperature (PST) and prescribed temperature of heat flux (PHF), are obtained in the form of kummer’s fuction. Effect of several parameters controlling the temperature distribution are shown graphically and discussed briefly. Some of important findings of our analysis obtained by graphical representation are listed below.

1. Effect of viscoelastic parameter is to increase the temperature distribution in flow region in both cases PST and PHF. Hence viscoelastic fluid having low viscous dissipation must be chosen for effecting cooling of stretching Sheet.
2. The energy dissipation (being indicated by the Eckert number) due to heating, viscous dissipation and deformation work has the effect to thicken the thermal boundary layer increases in the temperature profile, and hence reduce the heat transfer rate from the surface.
3. The effect of Prandtl number is to decrease the thermal boundary layer thickness.
4. The effect of space and temperature dependent heat source/sink parameters is to generate temperature for increasing values and absorb for decreasing values. Hence non-uniform heat parameters are better suited for cooling purpose.

Acknowledgements

Prashant G Metri is grateful to Erasmus Mundus project FUSION (“Featured Europe and south-east Asia mobility Network”) for support and to the Division of Applied Mathematics, School of Education, Culture and Communication at Mälardalen University for creating excellent research environment during his visit and work on this paper.

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