

Flow and Heat Transfer of Maxwell Fluid with Variable Viscosity and Thermal Conductivity over an Exponentially Stretching Sheet

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Abstract In this paper we investigate effects of variable viscosity and variable thermal conductivity on the steady flow and heat transfer of Maxwell fluid over an exponentially stretching sheet. Momentum equation and energy equation are solved numerically using an implicit finite-difference scheme known as Keller-box method. The numerical solutions for the wall skin friction coefficients, heat transfer coefficient and the velocity and temperature profiles are computationally analyzed and discussed through graphs and tables. Here Prandtl number also treated as variable because it depends on variable viscosity and variable thermal conductivity. It is found that skin friction coefficient and heat transfer coefficient are lower for the Maxwell fluid of constant viscosity and thermal conductivity.

Keywords Maxwell Fluid, Exponentially Stretching Sheet, Variable Prandtl Number, Variable Viscosity, Variable Thermal Conductivity

1. Introduction

The flow and heat transfer analysis in the boundary on a continuously moving or stretching surface has wide important applications in many polymer industries and several manufacturing processes such as glass-fiber and paper production, drawing of plastic films, wire drawing, manufacturing of polymeric sheets and polymer extraction of plastic sheets. During the manufacture of these sheets, the melt substance passing through a slit and is subsequently stretched to achieve the desired thickness[see Fig.1]. The mechanicals properties of the final product is regulated by the extensibility of the sheet, rate of cooling (depending on physical property of the cooling medium e.g. thermal conductivity) and rheological properties (like viscosity which determines drag required to pull the sheet) of the fluid.

Since the pioneering study by Crane[7] who presented an exact analytical solution for the study of two-dimensional stretching of a surface with a velocity proportional to the distance from the origin, many authors[3,10,11,20] have considered various aspects of this problem and obtain similarity solutions. Some authors[6,13,22] have studied the boundary layer flow of heat transfer by taking non-linear stretching sheet. Elbashbeshy[8], Magyari and Keller[15]

and Sanjayanand and Khan[19] have studied the flow, heat transfer and mass transfer of a viscoelastic fluid over an exponentially stretching sheet. Singh and Agarwal[21] extended the work of Khan and Sanjayanand[12]. They have analyzed the influence of magnetic field on flow field and heat transfer for a second grade fluid over an exponentially stretching sheet with radiation and elastic deformation through graphs and tables.

Eldabe and Mohamed[9] have investigated the heat and mass transfer occurring in the magnetohydrodynamic flow of the non-Newtonian fluid (Walter's liquid B) through porous medium on a linearly accelerating surface with temperature dependent heat source subject to suction or blowing. They presented a series solution to the energy equation and concentration equation in terms of Kummer's function. Able and Mahesha[1] have studied the influence of variable thermal conductivity with temperature dependent heat source/sink, in the presence of thermal radiation. Vajravelu and Rollins[23] have investigated the flow and heat transfer in electrically conducting fluid over a stretching surface. Prasad et al.[16] have studied the effect of thermal radiation on MHD viscoelastic fluid flow and heat transfer of Walter's liquid-B past a stretching sheet with variable fluid viscosity and variable thermal conductivity.

Aliakbar[2] investigated the MHD flow and heat transfer of a UCM, fluid above a semi-infinite stretching sheet with viscous dissipation and Radiative heat transfer. For finding an analytic solution they have used homotopy analysis method. Prasad et al.[17] have theoretically studied the

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Published online at <http://journal.sapub.org/ajfd>

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effects of the temperature-dependent viscosity and thermal conductivity on the MHD boundary layer flow and heat transfer of a UCM fluid over a linear stretching sheet.

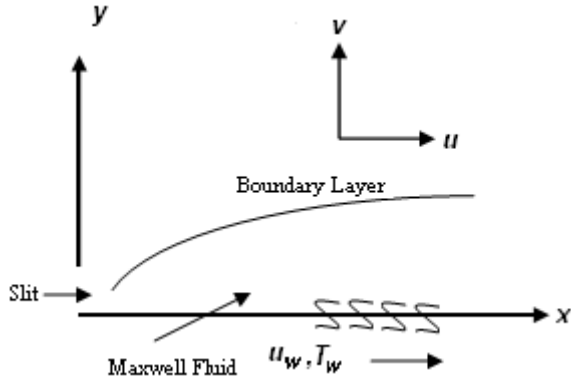


Figure 1. Physical model and co-ordinate system

Rahman and Salahuddin[18] have investigated the MHD heat and mass transfer flow over a radiative isothermal

inclined heated surface with variable viscosity and electric conductivity. In this research we have attempted to solve the problem that involves the flow and heat in the presence of suction/blowing with variable viscosity and variable thermal conductivity (Prandtl number is also variable inside the boundary layer), to the best of our knowledge which has never been explored before.

2. Mathematical Formulation

Let us consider a steady 2-D boundary layer flow of a viscous incompressible upper convected Maxwell fluid over an exponentially stretching sheet. The sketch of the physical configuration and co-ordinate system are shown in Fig. 1.

The boundary layer equations of the fluid flow and energy in the presence of variable fluid properties (fluid viscosity and thermal conductivity) can be written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \lambda \left[u^2 \left(\frac{\partial^2 u}{\partial x^2} \right) + v^2 \left(\frac{\partial^2 u}{\partial y^2} \right) + 2uv \left(\frac{\partial^2 u}{\partial x \partial y} \right) \right] = \frac{1}{\rho} \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) \quad (2)$$

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) \quad (3)$$

where u and v are the components of velocity in x and y axis respectively, c_p is the specific heat at constant pressure and ρ is the fluid density (assumed constant).

Let us consider the temperature dependent thermal conductivity $k(T)$ vary as the linear function of temperature[5] and temperature dependent coefficient of viscosity $\mu(T)$ vary as inverse function of temperature[14] such as

$$k = k_\infty \left[1 + \varepsilon \left(\frac{T - T_\infty}{T_w - T_\infty} \right) \right] \quad (4)$$

where ε is the small parameter, k_∞ is the conductivity of the fluid far away from the sheet, T_w is the wall temperature, T_∞ is the temperature far away from the sheet and

$$\frac{1}{\mu} = \frac{1}{\mu_\infty} \left[1 + r(T - T_\infty) \right] \quad (5a)$$

$$\text{i.e. } \frac{1}{\mu} = a(T - T_r) \quad (5b)$$

$$\text{where } a = \frac{r}{\mu_\infty} \text{ and } T_r = T_\infty - \frac{1}{r} \quad (5c)$$

Here a and T_r are the constants and their values depend on reference state, and r is the thermal property of the fluid. Generally for the liquids $a > 0$ and for gases $a < 0$.

The boundary conditions for the velocity components and temperature are given by

$$u = u_w(x), \quad v = v_w(x), \quad T = T_w(x) \text{ at } y = 0 \quad (6a)$$

$$u \rightarrow 0, \quad T \rightarrow T_\infty \text{ at } y \rightarrow \infty \quad (6b)$$

The stretching velocity u_w , variable mass transfer velocity v_w and the exponential temperature distribution are defined as[4]

$$u_w(x) = u_0 e^{x/L} \quad (7a)$$

$$v_w(x) = v_0 e^{x/2L} \quad (7b)$$

$$T_w(x) = T_\infty + Be^{bx/2L} \quad (7c)$$

where u_0 is reference velocity, L is the reference length, v_0 is constant with $v_0 < 0$ for suction and $v_0 > 0$ for injection and B is a constant depending on the thermal property of the liquid. The above exponential boundary condition is valid only when $x \ll L$, which occurs very near to the slit.

Equations (2) and (3) can be changed into ODE by introducing the following non dimensional variables.

$$\psi(x, y) = \sqrt{2v_\infty Lu_0} f(x, \eta) e^{x/2L} \quad (8a)$$

$$\eta = y \sqrt{\frac{u_0}{2v_\infty L}} e^{x/2L} \quad (8b)$$

$$\theta = \frac{T - T_\infty}{T_w - T_\infty} \quad (8c)$$

where $\psi(x, y)$ is the stream function f is the dimensionless stream function and θ is the non-dimensional temperature.

Since $u = \frac{\partial \psi}{\partial y}$, and $v = -\frac{\partial \psi}{\partial x}$, the equation of continuity (1) is automatically satisfied.

With the help of equations (4), (5) and (8), Equation (2) gets reduced to,

$$2 \left[(f')^2 - \frac{f \cdot f''}{2} \right] + k^* \left[2(f')^3 + \frac{f^2 \cdot f'''}{2} - 3f \cdot f' \cdot f'' \right] = \frac{1}{\left(1 - \frac{\theta}{\theta_r}\right)} \left[f''' + \frac{3f''}{2} - \frac{f''\theta'}{\theta - \theta_r} \right] \quad (9)$$

where $k^* = \frac{\lambda u_0 e^{x/L}}{L}$ is the Maxwell parameter or viscoelastic parameter and $\theta_r = -\frac{1}{r(T_w - T_\infty)}$ is the fluid viscosity parameter (depends on viscosity/temperature characteristics of the fluid under consideration and the temperature difference).

We get the relation between constant viscosity and variable viscosity is $\mu = \mu_\infty \left(1 - \frac{\theta}{\theta_r}\right)^{-1}$.

Since the Prandtl number depends on variable viscosity and variable thermal conductivity therefore Prandtl number also varies as [18]

$$\text{Pr} = \frac{\mu c_p}{k} = \frac{\mu_\infty c_p \left(\frac{\theta_r}{\theta_r - \theta}\right)}{k_\infty (1 + \varepsilon \theta)}$$

$$\text{Pr} = \frac{\text{Pr}_\infty}{\left(1 - \frac{\theta}{\theta_r}\right)(1 + \varepsilon \theta)} \quad (10a)$$

$$\text{Pr}_\infty = \left(1 - \frac{\theta}{\theta_r}\right)(1 + \varepsilon \theta) \text{Pr} \quad \text{at } \eta = 0 \quad (10b)$$

where $\text{Pr}_\infty = \frac{\mu_\infty c_p}{k_\infty}$ is the Prandtl number related to constant viscosity.

From equation (10a) it is clear that for large θ_r ($\theta_r \rightarrow \infty$) and small ε ($\varepsilon \rightarrow 0$), $\text{Pr} \rightarrow \text{Pr}_\infty$. To reduce the energy equation (3) in ODE, use equations (4), (5), (6) and (8c) in equation (3) we get

$$(1 + \varepsilon \theta) \theta'' + \text{Pr}_\infty f \theta' - b \text{Pr}_\infty f' \theta + \varepsilon \theta^2 = 0 \quad (11)$$

This is the energy equation for the constant Prandtl number, and

$$(1 + \varepsilon \theta) \theta'' + \text{Pr}(1 + \varepsilon \theta) \left(1 - \frac{\theta}{\theta_r}\right) f \theta' - b \text{Pr}(1 + \varepsilon \theta) \left(1 - \frac{\theta}{\theta_r}\right) f' \theta + \varepsilon \theta^2 = 0 \quad (12)$$

is the energy equation for variable Prandtl number. It is clear from equation (12) large θ_r ($\theta_r \rightarrow \infty$) and small ε ($\varepsilon \rightarrow 0$), $(\theta/\theta_r) \rightarrow 0$. The equation (12) reduces into Equation (11).

The corresponding boundary conditions for the flow and temperature distribution are

$$f = s, f' = 1, \theta = 1 \text{ at } \eta = 0 \quad (13a)$$

$$f' \rightarrow 0, \theta \rightarrow 0 \text{ at } \eta \rightarrow \infty \quad (13b)$$

where $s = -\frac{v_0}{\sqrt{\frac{v_\infty u_0}{2L}}}$ is the mass transfer parameter.

$s > 0$ ($v_0 < 0$) corresponds suction and $s < 0$ ($v_0 > 0$) corresponds to the injection.

3. Numerical Method

The system of transformed governing equations (9) and (12) subject to the boundary conditions (13) is solved numerically using an implicit finite-difference scheme which is known as Keller box method. This method has second-order accuracy and unconditionally stable. In this method, the transformed differential equations were first rewritten as a system of first order equations and using central differences these equations are converted into a set of finite difference equations. The resulting non-linear system of equation is solved by using the Newton Quasi-linearization method. Finally the difference equations are solved using a block matrix algorithm.

4. Result and Discussions

In order to get a physical insight into the problem, extensive computations have been performed for the effects of the controlling thermofluid parameters on the

dimensionless velocity and temperature and also on the skin-friction and Nusselt number. These computational results are shown in Figs. 2-10. The graphs are drawn in the presence ($\theta_r \neq 0$) /absence ($\theta_r \rightarrow \infty$) of fluid viscosity parameter cases. The skin friction coefficient ($-f''(0)$) and wall temperature gradient ($-\theta'(0)$) are presented in table 1.

The effects of Maxwell parameter k^* on velocity components u - v (u along x axis called horizontal velocity and v along y axis called vertical velocity) are shown in Figs. 2(a) and 2(b). It is noted that $k^* = 0$ is for Newtonian fluid. It is evident from these figures that increase in the Maxwell parameter or elasticity parameter k^* is reduced the velocity profiles on both directions. This is due to the fact that with an increase in the Maxwell parameter k^* decreases the velocity boundary layer thickness which results in the decrease in the velocity profile for both cases ($\theta_r = -1$ and $\theta_r \rightarrow \infty$).

Figs. 3(a) and 3(b) shows the effects of suction/injection parameters s on velocity components in x and y directions respectively. It is clear from Fig 3(a) that as compared to an impermeable sheet ($s=0$), injection ($s<0$) has the effect to reduce the boundary layer thickness and thus the horizontal velocity, whereas suction ($s>0$) tends to thicken the boundary layer and the velocity increase accordingly in x direction while the trend reverse in y direction which shown in Fig. 3(b). This result is consistent with the physical situation.

Figs. 4(a) and 4(b) exhibit the velocity distribution in x and y directions for different values of variable fluid viscosity parameter θ_r . From these graphs we observe that the velocity profile decreases with increases in the variable fluid viscosity parameter θ_r as compared to constant fluid viscosity parameter ($\theta_r \rightarrow \infty$). This is due to the fact that increase of the viscosity/temperature parameter θ_r makes decreases of the boundary layer thickness which results in decrease of the velocity along both directions.

Table 1. Values of skin friction coefficient ($-f''(0)$) and wall temperature gradient ($-\theta'(0)$) for different values of pertinent parameters

| k^* | s | b | ε | Pr | θ_r | $-f''(0)$ | $-\theta'(0)$ |
|-------|------|-----|---------------|------|------------|-------------|---------------|
| 0.0 | 0.0 | 2.0 | 0.1 | 3.0 | -1.0 | 3.045072950 | 2.576718476 |
| 0.2 | | | | | | 3.161126386 | 2.554396272 |
| 0.4 | | | | | | 3.271006259 | 2.533471128 |
| 0.6 | | | | | | 3.375615292 | 2.513716491 |
| 0.8 | | | | | | 3.475666385 | 2.494950377 |
| 0.0 | 0.0 | 2.0 | 0.1 | 3.0 | ∞ | 2.185079642 | 2.017609594 |
| 0.2 | | | | | | 2.274554275 | 1.996920462 |
| 0.4 | | | | | | 2.358760467 | 1.977467370 |
| 0.6 | | | | | | 2.438469684 | 1.959051237 |
| 0.8 | | | | | | 2.514280157 | 1.941518023 |
| 0.2 | -0.2 | 2.0 | 0.1 | 3.0 | -1.0 | 6.046615309 | 2.192012238 |
| | 0.0 | | | | | 3.161126386 | 2.554396272 |

| | | | | | | | |
|-----|------|------|------|-----|----------|-------------|--------------|
| | 0.2 | | | | | 5.018027124 | 2.988237034 |
| 0.2 | -0.2 | 2.0 | 0.1 | 3.0 | ∞ | 3.732177006 | 1.744085098 |
| | 0.0 | | | | | 2.274554275 | 1.996920462 |
| | 0.2 | | | | | 3.197749379 | 2.291180036 |
| 0.2 | 0.0 | -2.0 | 0.1 | 3.0 | -1.0 | 2.543583235 | -3.736848144 |
| | | -1.0 | | | | 2.842487115 | -0.385099747 |
| | | 0.0 | | | | 2.988993625 | 0.971941818 |
| | | 1.0 | | | | 3.087239587 | 1.865934772 |
| | | 2.0 | | | | 3.161126386 | 2.554396272 |
| 0.2 | 0.0 | -2.0 | 0.1 | 3.0 | ∞ | 2.274554275 | -1.257938514 |
| | | -1.0 | | | | 2.274554275 | 0.000001325 |
| | | 0.0 | | | | 2.274554275 | 0.842860824 |
| | | 1.0 | | | | 2.274554275 | 1.479625222 |
| | | 2.0 | | | | 2.274554275 | 1.996920462 |
| 0.2 | 0.0 | 2.0 | -0.2 | 3.0 | -1.0 | 3.216982909 | 3.194519647 |
| | | | -0.1 | | | 3.196510692 | 2.939283062 |
| | | | 0.0 | | | 3.177989946 | 2.729890105 |
| | | | 0.1 | | | 3.161126386 | 2.554396277 |
| | | | 0.2 | | | 3.145687135 | 2.404741803 |
| 0.2 | 0.0 | 2.0 | -0.2 | 3.0 | ∞ | 2.274554275 | 2.520140450 |
| | | | -0.1 | | | 2.274554275 | 2.311114655 |
| | | | 0.0 | | | 2.274554275 | 2.140025264 |
| | | | 0.1 | | | 2.274554275 | 1.996920462 |
| | | | 0.2 | | | 2.274554275 | 1.875100407 |
| 0.2 | 0.0 | 2.0 | 0.1 | 1.0 | -1.0 | 2.966349227 | 1.240863136 |
| | | | | 3.0 | | 3.161126386 | 2.554396272 |
| | | | | 5.0 | | 3.278245587 | 3.455221783 |
| 0.2 | 0.0 | 2.0 | 0.1 | 1.0 | ∞ | 2.274554275 | 0.926220914 |
| | | | | 3.0 | | 2.274554275 | 1.996920462 |
| | | | | 5.0 | | 2.274554275 | 2.733918513 |
| 0.2 | 0.0 | 2.0 | 0.1 | 3.0 | ∞ | 2.274554275 | 1.996920462 |
| | | | | | -10.0 | 2.386970722 | 2.057961919 |
| | | | | | -5.0 | 2.492067077 | 2.117627905 |
| | | | | | -1.0 | 3.161126386 | 2.554396272 |
| | | | | | -0.5 | 3.766227635 | 3.030410700 |

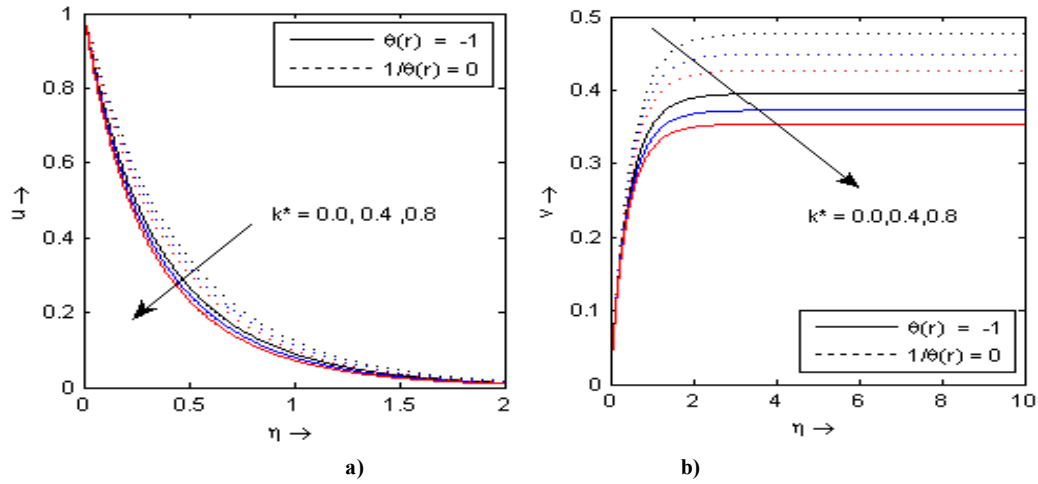


Figure 2. Velocity profiles for different values of Maxwell parameter k^* with $s=0$, $b=2$, $\varepsilon=0.1$, $Pr=3$

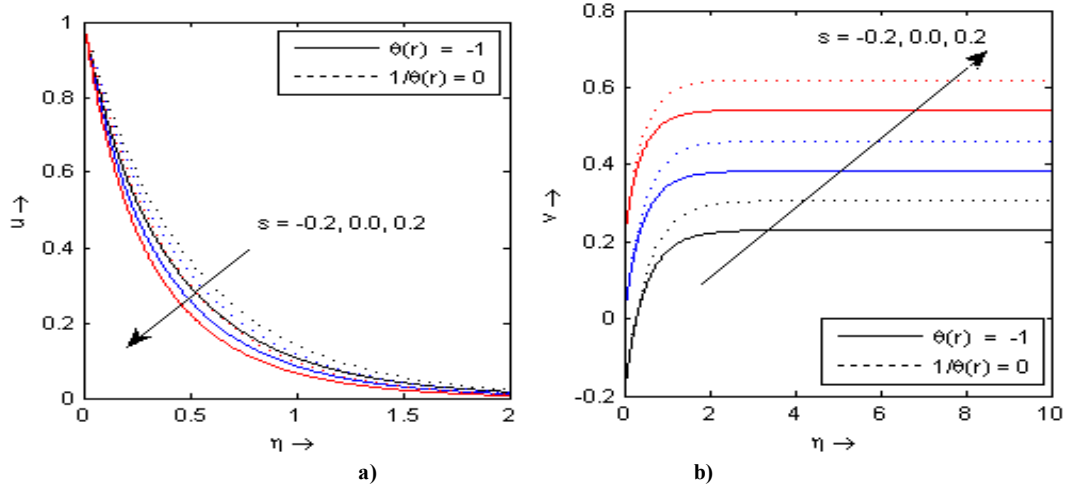


Figure 3. Velocity profiles for different values of suction/injection parameter s with $k^*=0.2$, $b=2$, $\varepsilon=0.1$, $Pr=3$

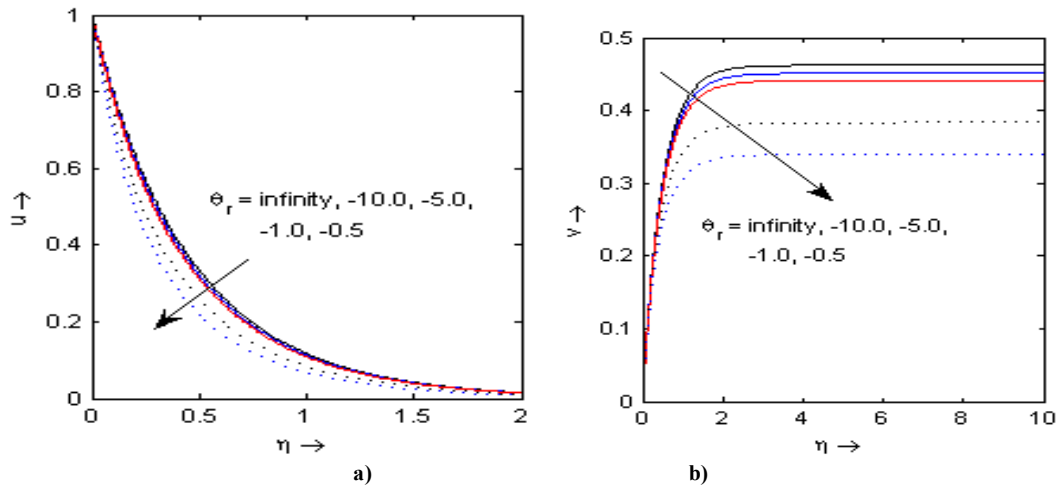


Figure 4. Velocity profiles for different values of variable fluid viscosity parameter θ_r with $k^*=0.2$, $s=0$, $b=2$, $\varepsilon=0.1$, $Pr=3$

Fig. 5 illustrates the effect of Maxwell parameter k^* on temperature profile $\theta(\eta)$ in both cases ($\theta_r=-1$ and $\theta_r \rightarrow \infty$). It is observe that temperature profile $\theta(\eta)$ increases with

increasing values of Maxwell parameter k^* because the thermal boundary layer becomes broadened as we increase Maxwell parameter k^* .

Fig. 6 depicts the effects of suction/injection parameter s on the temperature distribution. The thermal boundary layer becomes thicker for suction and thinner for blowing as compared to an impermeable sheet for both cases ($\theta_r = -1$ and $\theta_r \rightarrow \infty$). We may notice that the effect of suction/injection parameter is reversed with increase in the fluid viscosity parameter θ_r . The graph for the temperature profile $\theta(\eta)$ with η for different values of variable thermal conductivity parameter ε in the presence ($\theta_r = -1$) / absence ($\theta_r \rightarrow \infty$) of fluid viscosity parameter cases is shown in Fig. 7. It is noticed from this figure that an increase in the value of thermal conductivity parameter ε also increases temperature profile $\theta(\eta)$. This is due to the fact that the assumption of temperature-dependent thermal conductivity (linear form) implies a reduction in the magnitude of the transverse velocity by a quantity $\partial k(T) / \partial y$ as can be seen from the heat transfer equation. We may further notice that the effect of variable thermal conductivity is to reduce the temperature with increase in the fluid viscosity parameter θ_r .

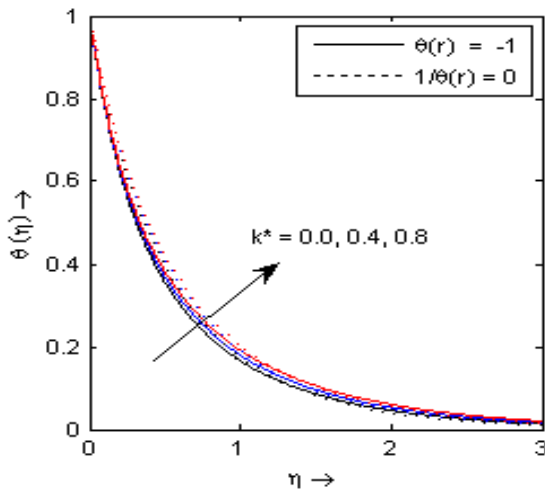


Figure 5. Temperature profile for different values of Maxwell parameter k^* with $s=0$, $b=2$, $\varepsilon=0.1$, $Pr=3$

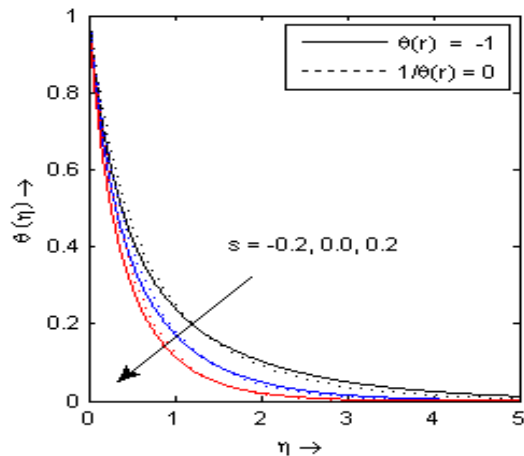


Figure 6. Temperature profile for different values of suction / injection parameter s with $k^*=0.2$, $b=2$, $\varepsilon=0.1$, $Pr=3$

The effects of power indices b on temperature profiles $\theta(\eta)$ with η may be analyzed from the Fig. 8 in both cases ($\theta_r = -1$ and $\theta_r \rightarrow \infty$). This graph depicts that an increase in the value of power indices b results in decrease the temperature profile $\theta(\eta)$. The variation of temperature profile $\theta(\eta)$ with η for various values of Prandtl number Pr presence ($\theta_r = -1$) / absence ($\theta_r \rightarrow \infty$) of fluid viscosity parameter cases are displayed in Fig. 9. This figure demonstrates that the increase of Prandtl number Pr (increase if Prandtl number Pr means decrease of thermal conductivity k_∞) results in decrease of temperature distribution which tend to zero as the space variable η increase from the wall and hence thermal boundary layer thickness decreases as Prandtl number Pr increases. This behaviour is observed in both the cases ($\theta_r = -1$ and $\theta_r \rightarrow \infty$). Near the boundary the thermal boundary layer thickness is higher at $\theta_r = -1$ (as compared to $\theta_r \rightarrow \infty$) and away from boundary, thermal boundary layer thickness is higher at $\theta_r \rightarrow \infty$ (as compared to $\theta_r = -1$).

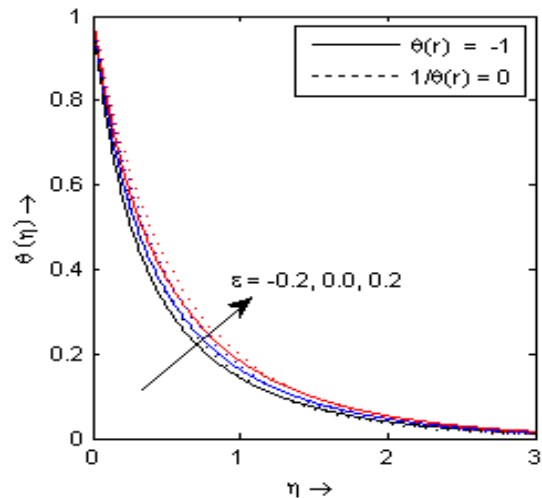


Figure 7. Temperature profile for different values of power index b with $k^*=0.2$, $s=0$, $\varepsilon=0.1$, $Pr=3$

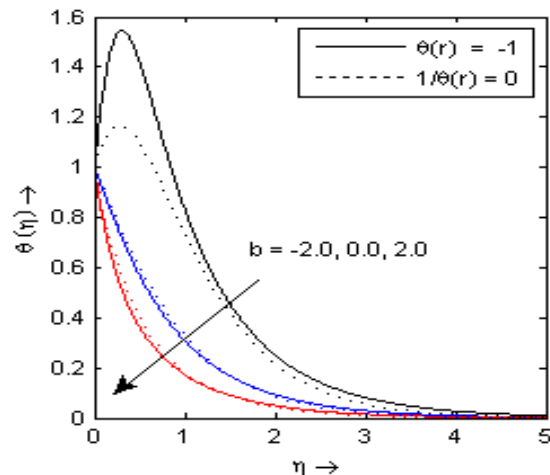


Figure 8. Temperature profile for different values of power index b with $k^*=0.2$, $s=0$, $\varepsilon=0.1$, $Pr=3$

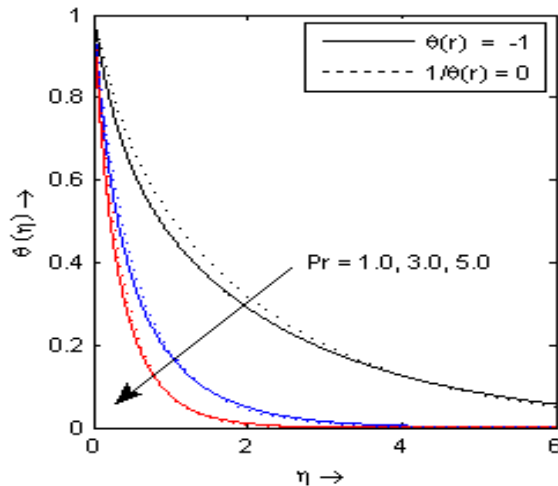


Figure 9. Temperature profile for different values of Prandtl number Pr with $k^* = 0.2$, $s=0$, $b=2$, $\varepsilon = 0.1$

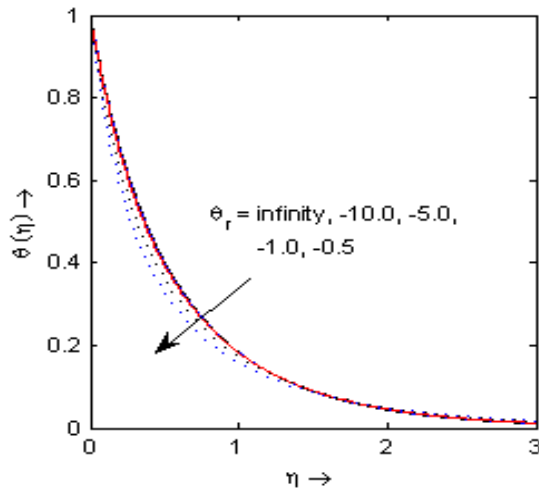


Figure 10. Temperature profile for different values of variable fluid viscosity parameter θ_r with $k^* = 0.2$, $s=0$, $b=2$, $\varepsilon = 0.1$, $Pr = 3$

Fig. 10 elucidate the effects of the variable fluid viscosity parameter θ_r on temperature profile $\theta(\eta)$. It is interesting to find from Fig.10 that when we increases the value of fluid viscosity parameter θ_r , temperature $\theta(\eta)$ becomes decreases because temperature dependent coefficient of viscosity $\mu(T)$ vary as inverse function of temperature.

5. Conclusions

The following conclusions have been made from the above work

1. The effect of Maxwell parameter is to decrease velocity distribution and to increase temperature distribution in the boundary layer.
2. It is observed that the velocity profiles decreases with the increase of the value of fluid viscosity parameter θ_r . Thus viscoelastic fluid must be chosen since it is having low viscous dissipation for effective cooling of the stretching sheet.
3. The velocity and temperature profiles in the case of constant viscosity are higher than the corresponding case of

variable viscosity.

4. The variable thermal conductivity also has an impact in enhancing the temperature profile, hence fluid with less thermal conductivity may be opted for effective cooling.

5. The effect of Prandtl number is to decrease the thermal boundary layer thickness.

6. The temperature profile is lower for injection parameter and higher for suction parameter.

ACKNOWLEDGEMENTS

The authors would like to thank the Council of Scientific and Industrial Research, New Delhi, for providing financial support through Grant No. 08/043(0005)/2008-EMR-I.

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