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Heat Transfer Across a Stretching Sheet in a Viscoelastic Boundary Layer with a Non-Uniform Heat Source and Viscous Dissipation

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Abstract- This work addresses visco-elastic boundary layer flow and heat transmission over a stretching sheet in the presence of viscous dissipation and a nonuniform heat source. Analytical solutions exist for highly non-linear momentum equations and heat transfer equations with confluent hypergeometric similarity. Here, two types of different heating procedures are considered: prescribed surface temperature (PST) and prescribed wall heat flux (PHF). A number of parameters, such as the visco-elastic parameter, Eckert number, Prandtl number, and non-uniform heat source/sink parameter, are analyzed in connection to the temperature distribution. Each of these parameters' effects on the wall temperature gradient and wall temperature are enumerated and described.

Keywords: Similarity solution, stretching sheet, viscoelastic liquid, non-uniform heat source/sink, viscous dissipation, and Eckert number.

I. INTRODUCTION

Sakiadis [1,2] started researching the boundary layer problem under the assumption that a boundary sheet's velocity is constant.

Many studies have been conducted on the two-dimensional visco-elastic boundary layer flow over a stretching surface, where the stretching surface's velocity is thought to be linearly proportional to the distance from a fixed origin.

Researchers are once again interested in studying viscoelastic boundary layer flow over a stretching plastic sheet due to the widespread use of viscoelastic fluids in various industrial manufacturing processes and (Rajagopal et al. [3,4], Dandapat and Gupta [5], Rollinsavelu [10], Andersson [6], Lawrence and Rao [7], Char [8], Rajagopal and Gupta [9], Rao [11], Bhattacharya et al. [13], and Vajravelu and Rollins [14]). The extrusion of polymer sheets from a dye, the production of glass fiber and paper, the drawing of plastic films, etc. are typical applications for this type of study.

The production of plastic films and synthetic fibers, aerodynamic plastic sheet extrusion, cooling metallic sheets in a cooling bath, crystal growth, liquid film condensation, continuous polymer sheet extrusion, heat-treated materials moving between feed rolls, wind-up rolls, or conveyer belts, geothermal reservoirs, and the petroleum industries are just a few of the numerous industrial processes that make extensive use of non-Newtonian liquids.

This has led to a further focus on non-Newtonian fluid flow in the research of the visco-elastic boundary layer flow problem. According to a review of the literature, Raja Gopal et al. [3] studied visco-elastic second-order fluid flow across a stretching sheet by numerically solving boundary layer equations; however, this work did not account for the phenomenon of heat transfer. Similar flow analysis without heat transfer in the non-Newtonian fluid flow of Walters' liquid has been examined by Siddappa and Abel [25].

Bujurke et al. [26] have investigated momentum and heat transfer phenomena in a visco-elastic second order fluid across a stretching sheet with internal heat generation and viscous dissipation. For the MHD flow of a viscoelastic liquid of Walters' liquid B past a stretched sheet, Andersson [6] offered an exact analytical solution. The literature contains numerous articles on viscoelastic boundary layer flow and heat transfer processes ([16–18, 20–24,27,31,32]), but their analysis only considers temperature-dependent heat sources and sinks.

Vajravelu and Nayfeh [15] studied transfer on a vertical sheet in a generating (absorbing) fluid.

The impact of varying viscosity on forced convection flow over a horizontal flat plate in a porous medium with internal heat generation was studied by Postelnicu et al. [28], however they only took into account space-dependent heat sources in the heat generation section. Once more, Postelnicu et al. [29] examined the free convective boundary layer over a vertical permeable plate in a porous medium with internal heat generation, but they only took space-dependent heat generation into account. In their study of the similarity solutions of free convective boundary layers over vertical and horizontal surfaces in porous media with internal heat generation, Postelnicu et al. [30] once again focused solely on space-dependent heat generation.

Postelnicu et al. [28–30] only considered space-dependent internal heat generation and viscous flow in all of these investigations. However, Abo-Eldahab and El Aziz [12] considered the blowing/suction effect on hydro magnetic heat transport via mixed convection from an angled continuously expanding surface with internal heat generation/absorption. Nonetheless, the work considered the heat source/sink in a viscous flow that is reliant on both space and temperature .The aforementioned literature does not address the effect of non-uniform heat generation on the heat transfer processes in visco-elastic boundary liquid flow. Heat transmission mechanisms in non-Newtonian fluid flows, as Walters' liquid B, are significantly impacted by frictional heating.

Thus, taking into consideration frictional heating and non-uniform heat sources, we intend to investigate in this work the non-Newtonian visco-elastic boundary layer flow of Walters' liquid B past a stretched sheet (Abo-Eldahab and El Aziz [12]). The properties of heat transmission are examined under two different boundary conditions: (i) when the wall is maintained at a certain power law temperature, and (ii) when the wall is maintained at a power law heat flux. Solution for analytical flow. and heat transport are determined as a confluent hypergeometric function known as Kummer's function.

Mathematical formulation and solution

When a semi-infinite, impermeable flat sheet that aligns with the plane is present

y = 0, consider the steady two-dimensional laminar flow of an incompressible visco-elastic fluid (following Walter's model), with the flow being restricted to y > 0. The surface is extended while the origin remains stationary by applying two equal and opposing forces along the x-axis. The fundamental boundary layer equations controlling the flow of Walters' Liquid B can be expressed as follows under the standard boundary layer assumptions:

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

$$\mathrm{u}\ \frac{\partial u}{\partial x} + \mathrm{v}\frac{\partial v}{\partial y} = \mathrm{v}\frac{\partial^2 u}{\partial y^2} - \mathrm{k}_0 \left\{ \mathrm{u}\frac{\partial^3 u}{\partial x \partial y^2} + \mathrm{v}\frac{\partial^3 u}{\partial y^3} + \frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2} - \frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x \partial y} \right\}$$

Where u and v are the velocities along the x and y directions, respectively, and x and y stand for the horizontal and transverse directions, respectively. The kinematic viscosity is denoted by t, while the viscoelasticity coefficient is denoted by k0. These equations are derived under the assumption that the normal stress contribution is of the same order of magnitude as the shear stress, in addition to the conventional boundary layer assumptions. Consequently, t and k0 are on the order of the squared boundary layer thickness.

The boundary conditions are

$u_w (x) = b_x$, $v| = 0$, at $y = 0$,

$u \to 0$, as $y \to \infty$

With b > 0, this is known as stretching rate. Equation (1) and (2), subjected to boundary condition (3), admit self-similar solution in terms of the similarity function f and the similarity variable g defined by

$u = b_x f_n (n)$, $v = -\sqrt{bvf(n)}$, $n = \sqrt{\frac{b}{v}}\ y$,

Where suffix denotes the derivative w.r.t *n*. Clearly u and v as defined above satisfy the continuity equation (1) and (2) becomes

$$f_\eta^2 - ff_{\eta\eta} = ff_{\eta\eta\eta} - \mathrm{k}_1 \{2f_\eta f_{\eta\eta\eta} - ff_{\eta\eta\eta} - f_{\eta\eta}^2\}$$

Where $k_1 = \frac{k_{0b}}{v}$, is the visco-elastic parameter. Similarly boundary conditions (Eq. (3)) become,

$$f_\eta(\eta) = 1, \; f(\eta) = 0 \text{ at } \eta = 0,$$
$$f_\eta(\eta) \to 0, \text{ as } \eta \to \infty$$

It should be emphasized that solving Eq. (5) uniquely requires more than only the boundary condition Eq. (6). Therefore, Raja Gopal et al. [4] used boundary condition Eq. (6) to derive the corresponding solution of Eq. (5), which is an accurate solution of Eq. (5), satisfying the boundary requirements (6) and is given by

$$f(\eta) = \frac{1-e^{-\alpha\eta}}{\alpha}, \text{ with } \alpha = \sqrt{\frac{1}{1-k_1}}$$

Obviously, $0 < k_1 < 1$.

Therefore, the velocity components are

$u = b_x e^{-\alpha\eta}$, and $v = -\sqrt{bv}\ \left(\frac{1-e^{-\alpha\eta}}{\alpha}\right)$

In the Section 3 we consider the heat transfer in the considered flow.

III. HEAT TRANSFER

Because the fluid under consideration in the analysis is viscoelastic, frictional heating from viscous dissipation will store the energy in the fluid. Thus, we consider this. Nonetheless, we believe that a fluid has more viscous than elastic properties. Additionally, while the momentum boundary layer equation is applicable at low shear rates and small values of the elastic parameter, the effect of elastic deformation terms may not be sufficient [3,5,18]. Because of this, we can exclude the heat energy contribution resulting from elastic deformation. Therefore, for two-dimensional flow with viscous dissipation and non-uniform internal heat generation/absorption, the governing boundary layer heat transfer equation is

$$pc_p \left(u\frac{\partial T}{\partial x} + v\,\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} + \mu\left(u\frac{\partial u}{\partial y}\right) + q'''$$

Where q0 is the space- and temperature-dependent internal heat generation/absorption (nonuniform heat source/sink) [12], where k is the thermal conductivity, q is the density, T is the temperature, cp is the specific heat at constant pressure, l is the viscosity, and

$$q = \left(\frac{ku_w(x)}{xv}\right)[A * (T_w - T_\infty)\, f'(\eta) + B^*(T - T_\infty)]$$

Where A* and B* are internal heat generation/absorption characteristics that depend on temperature and space. Notably, internal heat creation is represented by A* > 0 and B* > 0, whereas internal heat absorption is represented by A* < 0 and B* < 0. The type of boundary conditions specified determines how Eq. (9) is solved. As will be covered below, two kinds of heating procedures are taken into consideration.

Case A: Prescribed power law surface temperature (PST case)

The required surface temperature for this heating process is determined by assuming that it is a quadratic function of x.

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

Where T_w is the temperature of the wall and T_1 is the temperature outside the dynamic region. The constant A depends on the thermal properties of the liquid and $l = \sqrt{\frac{v}{b}}$ is a characteristic length. We now define a dimensionless scaled temperature as

$$\theta(\eta) = \frac{T - T_\infty}{Tw - T_\infty}$$

Where $Tw - T_\infty = A\left(\frac{x}{l}\right)^2\ \theta(\eta)$

Eq. (9) on using Equation (11) and (12) can be transformed to the following equation

$$\theta_{\eta\eta}(\eta) + Prf(\eta) - (2Prf_\eta(\eta) - B^*)\,\theta(\eta)$$
$$- (EPrf_{\eta\eta}^2 + A^* f_\eta),$$
$$f_\eta(\eta) \to 0, \text{ as } \eta \to \infty$$

Where $E = \frac{b^2 l^2}{ACp}$ (Eckert number), $Pr| = \frac{\mu c_p}{k}$ (Prandtl number).

Using Eq. (12) in Eq. (13) the boundary conditions read as

$$\theta(\eta) = l \text{ at } \eta = 0$$
$$\theta(\eta) \to 0 \text{ at } \eta \to \infty$$

In terms of hypergeometric Kummer's function [19], the solution of Eq. (13), subject to boundary constraints (14), can be found as

$$\theta(\eta) = c_1\,(e^{-\alpha\eta})^{\frac{a_0+b_0}{2}}\ M\ \left(\frac{a_0+b_0}{2} - 2, 1 + b_0, -\frac{Pr}{\alpha^2}e^{-\alpha\eta}\right)$$
$$+ c_2\,e^{-\alpha\eta} + c_3\,e^{-2\alpha\eta}$$

Where

$a_{0,} - \frac{Pr}{\alpha^2}$, $b_{0,} = \sqrt{a_0^2 - \frac{4B*}{\alpha^2}}$, $c_1 = \frac{1-(c_1+c_2)}{M(\frac{a_0+b_0}{2}-2,1+b_{0,}-\frac{Pr}{\alpha^2})}$

$c_2 = \frac{-A*}{(4\alpha^2-2Pr+B*)}$ And $c_3 = \frac{-E\alpha^2 Pr}{(4\alpha^2-2Pr+B*)}$

The non-dimensional wall temperature gradient derived from Eq. (15) reads as

$$\theta(0) = c_1\left[-a\left(\frac{a_0+b_0}{2}\right) M\left(\frac{a_0+b_0-4}{2}, 1 + b_0; -\frac{Pr}{\alpha^2}\right) + \left(\frac{a_0+b_0-4}{2(1+b_0)}\right)\frac{Pr}{a} M\left(\frac{a_0+b_0-2}{2}, + b_0; -\frac{Pr}{\alpha^2}\right)\right] - c_2 a - c_3 a$$

Case B: Power law surface heat flux prescribed (PHF instance)

The power law heat flux on the wall surface is considered to be a quadratic power of x in the form

$-\mathrm{k}\frac{\partial^2 T}{\partial y^2} = q_w = \mathrm{D}\,(\frac{x}{l})^2$ at y = 0,

$\mathrm{T} \rightarrow T_\infty \quad as\ y \rightarrow \infty$

If l is as previously defined, k is the heat conductivity, and D is a constant. A dimensionless, scaled temperature g(η) is now defined as

$\mathrm{g}(\eta) = \frac{T - T_\infty}{T_w - T_\infty}$,

Where

$T_w - T_\infty = \frac{D}{k}(\frac{x}{l})^2 \sqrt{\frac{v}{b}}$

Using Equation. (17) And (18), (9) can be written in terms of g as

$g_{\eta\eta}(\eta) + \mathrm{Pr} f(\eta) g_\eta(\eta) - (2Prf_\eta(\eta) - B^*)\, g(\eta) = -(EPrf_{\eta\eta}^2 + \mathrm{A}^* f_\eta)$,

Where $\mathrm{E} = \frac{k\, b^2 l^2 \sqrt{\frac{b}{v}}}{DCp}$ (Eckert number) and the boundary conditions

Take the form

$g_\eta(\eta) = -1$ at $\eta = 0$,

$g_\eta(\eta) \rightarrow 0$ at $\eta \rightarrow \infty$,

With f(η) as defined earlier in the PST case. The solution of Eq. (20), subject to the boundary condition (21), can be obtained in terms of hypergeometric Kummer's function [19] in the form

$$g_\eta(\eta) = c_{4\,e^{-\alpha}} \left(\frac{a_0+b_0}{2}\right)\eta \quad M\left(\frac{a_0+b_0}{2} - 2, 1 + b_0; -\frac{Pr}{\alpha^2} e^{-\alpha\eta}\right) + c_{2\,e^{-\alpha\eta}} + c_{3\,e^{-2\alpha\eta}}$$

Where a₀, b₀, c₂ and c₃ are as defined earlier in the PST case and c₄ is given by

$$c_4 = \frac{c_2+2c_3)\,\alpha-1}{\left[-a\left(\frac{a_0+b_0}{2}\right) M\left(\frac{a_0+b_0-4}{2}, 1+ b_0; -\frac{Pr}{\alpha^2}\right) + \left(\frac{a_0+b_0-4}{2(1+b_0)}\right)\frac{Pr}{a} M\left(\frac{a_0+b_0-2}{2}, 2+ b_0; -\frac{Pr}{\alpha^2}\right)\right]}$$

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

$$g(0) = c_{4\ M}\left(\frac{a_0+b_0}{2} - 2, 1 + b_0; -\frac{Pr}{\alpha^2}\right) + c_2 + c_3$$

Now we proceed to the discussion of results of the undertaken study.

IV. FINDINGS AND CONVERSATION

This work investigates a boundary layer problem for momentum and heat transmission in viscoelastic fluid flow across a stretching sheet with a spatial and temperature dependent heat source. For two general situations of boundary conditions, namely (i) PST Case and (ii) PHF Case, the boundary layer equations of momentum and heat transfer are solved analytically, and various analytical expressions for non-dimensional temperature profiles are produced. Additionally, dimensionless temperature gradients θ (0) and g(0) have explicit analytical expressions. Figs. 1–5 show numerical simulations of the conclusions for the PST and PHF situations, respectively.

. Viscoelastic parameter k1, Prandtl number Pr, Eckert number E, space-dependent heat source/sink parameter A*, and temperature-dependent heat source/sink parameter B* are the parameters that emerge in the study. We are familiar with the parameters k1, E, and Pr. A* and B* are not very big numbers. We now move on to the outcomes discussion.

For the PST scenario, Fig. 1(a) shows the temperature profile θ (η) vs η from the sheet for various values of

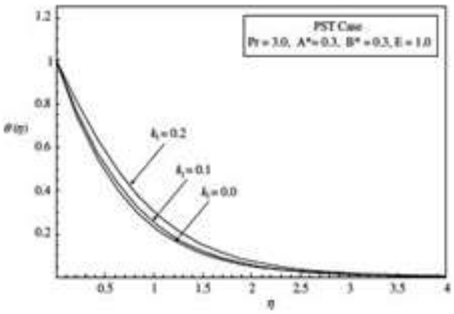

Fig. 1(a). Effect of visco-elasticity (k1) on temperature distribution in PST case.

For various values of k1, the temperature profile g(η) vs η for the PHF scenario is shown graphically in Fig. 1(b). These figures show that, in the PST situation, the temperature at the wall remains constant despite changes in physical characteristics. In both the PST and PHF cases, we also note that the temperature rises as the value of k1 grows.

This is because a thickening of the thermal boundary layer results from an increase in visco-elastic normal stress.

The temperature profiles h(η) and θ (η) vs η from the sheet, for various values of Pr, are shown in Figs. 2(a) and 2(b). These numbers suggest that the viscous boundary layer is thicker than the thermal boundary layer since the temperature drops as Pr increases. In the free stream region, the temperature asymptotically approaches zero in both PST and PHF scenarios.

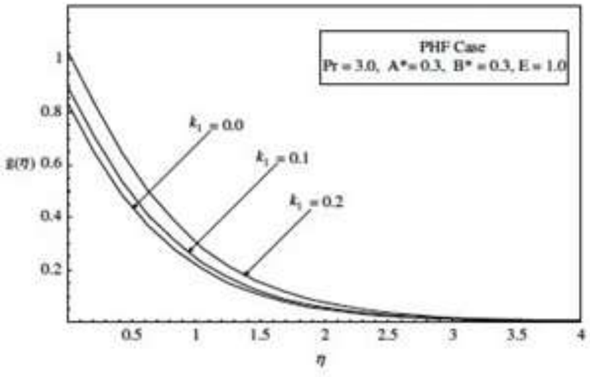

Fig. 1(b). Effect of visco-elasticity (k_1) on temperature distribution in PHF case.

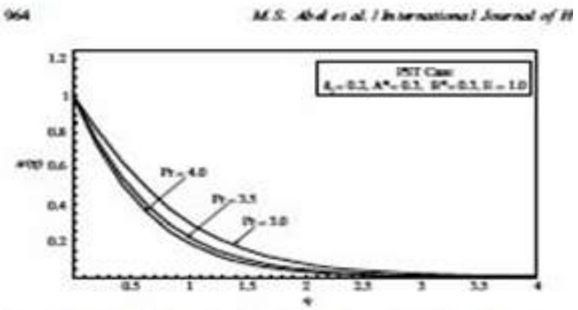

Fig. 2(a). Effect of Prandtl number (Pr) on temperature distribution in PST case.

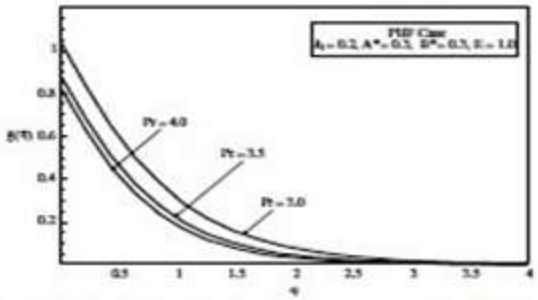

Fig. 2(b). Effect of Prandtl number (Pr) on temperature distribution in PHF case.

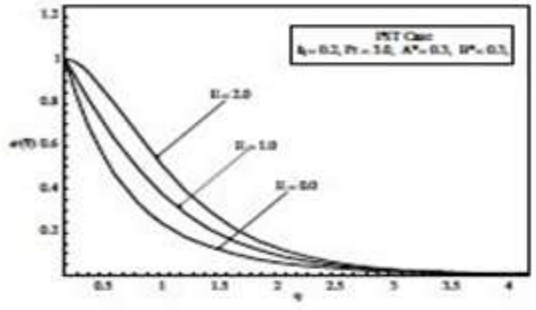

Fig. 3(a). Effect of Eckert number (E) on temperature distribution in PST case.

The Figs. 3(a) and 3(b) show the temperature distribution θ (η) and g(η) versus η from the sheet, for different values of Eckert number (E) for both PST and PHF cases, respectively The graphs show that, in both PST and PHF scenarios, rising values of E have the effect of raising the temperature distribution in the flow region. This is because the frictional heating causes heat energy to be stored in the liquid. In all scenarios, raising E has the effect of raising the temperature at all times.

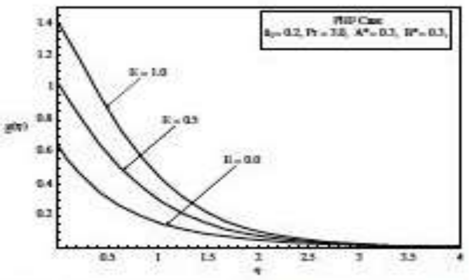

Fig. 3(b). Effect of Eckert number (E) on temperature distribution in PHF case.

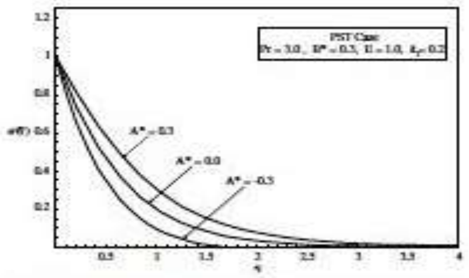

Fig. 4(a). Effect of non-uniform heat source/sink parameter (A*) on temperature distribution in PST case.

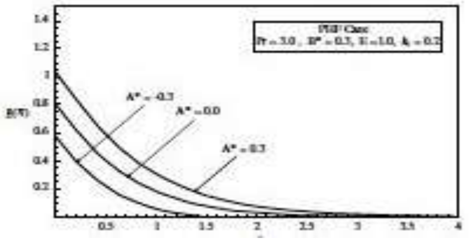

Fig. 4(b). Effect of non-uniform heat source/sink parameter (A*) on temperature distribution in PHF case.

Table 1

Value of wall temperature gradient θ(0) (for PST Case) and wall temperature g(0) (for PHF Case), for different values of E, k1, Pr, A* and B*

E	K_1	Pr	A*	B*	PST case θ(0)	PSF case g(0)
0.0	0.20	4.0	0.30		2.65822	0.41832
0.02				0.30	2.59404	0.426306
0.50					1.05386	0.617967
	0.00	4.0	0.30			
0.02	0.10				2.68986	0.406411
	0.20			0.30	2.65168	0.414147
					2.59404	0.426306
		3.0	0.30			
0.02	0.20	3.5			1.71759	0.652451
		4.0		0.30	2.29203	0.488533
			0.30		2.59404	0.426306
0.02	0.20	4.0	0.0			
			0.30	0.30	2.97909	0.291268
					2.78657	0.358772
0.02	0.20	4.0	0.30		2.59404	0.426306
				0.30	2.73959	0.4015
				0.0	2.66907	0.4131
				0.30	2.59404	0.4263

The outcomes are consistent with what occurs in areas other than the sheet.

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