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Unsteady Boundary Layer Flow past a Stretching Plate and Heat Transfer with Variable Thermal Conductivity

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ABSTRACT

An unsteady boundary layer flow of viscous incompressible fluid over a stretching plate has been considered to solve heat flow problem with variable thermal conductivity. First, using similarity transformation, the velocity components have been obtained, and then the heat flow problem has been attempted in the following two ways: 1) prescribed stretching surface temperature (PST), and 2) prescribed stretching surface heat flux (PHF) Flow and temperature fields have been analyzed through graphs. The expressions for skin friction and coefficient of convective heat transfer Nusselt number in PST and PHF cases have been derived.

Keywords: Unsteady Boundary Layer Flow; Skin Friction Energy Equation; Nusselt Number

1. Introduction

Due to number of applications in industrial manufacturing process, the problem of boundary layer flow past a stretching plate has attracted considerable attention of researchers during the past few decades. Examples of such technological process are hot rolling, wire drawing, glass-fiber and paper production. In the process of drawing artificial fibers the polymer solution emerges from orifice with a speed which increases from almost zero at the orifice up to a plateau value at which remains constant. The moving fiber, which is of great technical importance, is governed by the rate at which the fiber is cooled and this, in turn affects the final properties of the yarn. A number of works are presently available that follow the pioneering classical work of Sakiadis [1], F. K. Tsou, E. M. Sparrow, R. J. Goldstein [2] and Crane [3]. **Table 1** lists some relevant works that pertain to cooling liquids, *i.e.*, heat transfer for stretching surface.

There are liquid metals whose thermal conductivity varies with temperature in an approximately linear manner in the range from 0°F to 400°F. In 1996, T. C. Chiam [21] considered heat transfer problem with variable thermal conductivity in stagnation-point flow towards stretching sheet. Naseem Ahmad and Kavita Marwah [22] also studied boundary layer flow of Walters Liquid B Model with heat transfer for linear stretching plate with variable conductivity numerically. In 2010, Ahmad and Mishra investigated unsteady boundary layer flow and heat transfer over a stretching sheet [23].

In almost all the problems of stretching sheet with heat transfer where closed form solution is obtained, the thermal conductivity of liquid has been taken constant. The present paper is the extension of the work done by N. Ahmad and M. Mishra [23] assuming that the thermal conductivity varies in linear manner with temperature. The temperature field has two parts: one mean temperature, other is due to variable thermal conductivity. Both the parts mean temperature and temperature due to variable thermal conductivity have been analyzed thoroughly for some new recommendations.

2. Mathematical Formation and Solution

The problem considered here is the unsteady boundary layer flow due to a stretching flat plate in a quiescent viscous incompressible fluid. The flow is two dimensional where x-axis is along the plane of moving plate and y-axis is normal to it, respectively. We assume that the surface is moving continuously with the velocity $u_s = \dfrac{bx}{1-at}$; $a, b \in R^+$ and $t < 1/a$ in the positive x-direction. Under these assumptions, the boundary layer flow along moving plate is governed by the equations

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \tag{2.1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial x^2} \tag{2.2}$$

Table 1. Some relevant works that pertain to cooling liquids.

Author/s	Type of visco-elastic fluid	Remarks
K. R. Rajagopal, T. Y. Na, A. S. Gupta [4]	Second order fluid	Not heat transfer
K. R. Rajagopal, T. Y. Na, A. S. Gupta [5]	Second order fluid	Not heat transfer
N. M. Bujurke, S. N. Biradar, P. S. Hiremath [6]	Second order fluid	Heat transfer
B. S. Dhanpat, A. S. Gupta [7]	Second order fluid	Heat transfer
N. Ahmad, G. S. Patel and B. Siddappa [8]	Walter's liquid B	Heat transfer
D. Rollins, K. Vajravelu [9]	Second order fluid	Heat transfer
N. Ahmad, G. S. Patel, B. Siddappa [10]	Walter's liquid B	Heat transfer
S. P. Lawrence, N. B. Roa [11]	Second order fluid	Heat transfer
M. I. Char [12]	Second order fluid	Heat transfer
A. Naseem [13]	Walter's liquid B	Heat transfer
N. Ahmad [14]	Walter's liquid B	Heat transfer
D. Kelly, K. Vjravelu, L. Andrews [15]	Walters' liquid B	Heat transfer
N. Ahmad, K. Marwah [16]	Walter's liquid B	Heat transfer
A. M. subhas, A. Joshi, R. M. Sonth [17]	Walter's liquid B	Heat transfer
R. M. Sonth, S. K. Khan, A. M. Subhas [18]	Walter's liquid B	Heat transfer
Siddheshwar, Mahabaleswar [19]	Walter's liquid B	Heat transfer
M. Subhas Abel, P. G. Siddheshwar, Mahantesh M. Nandeppanavar [20]	Walter's liquid B	Heat transfer

where u, the horizontal velocity component; v, the vertical velocity component; ν, the kinematic viscosity

The relevant boundary conditions are:

$$y = 0,\ u = u_s,\ v = 0$$
$$y \to \infty,\ u = 0$$

Introducing the dimensionless variables

$$\bar{x} = \frac{x}{h};\ \bar{y} = \frac{y}{h};\ \bar{u} = \frac{uh}{v};\ \bar{v} = \frac{vh}{v};\ \bar{t} = \frac{tv}{h^2}$$

the Equations (2.1) and (2.2) reduce to

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \tag{2.3}$$

$$\frac{\partial u}{\partial t} + \upsilon \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} \tag{2.4}$$

with boundary conditions

$$\begin{aligned} y = 0, u = u_s, v = 0 \\ y \to \infty, u = 0 \end{aligned} \tag{2.5}$$

where bar has been dropped for convenience.

Setting the similarity solution of the form

$$u = \frac{bx}{1-at} f'(y)$$ and using continuity equation, we have

$$v = -\frac{b}{1-at} f(y) \tag{2.6}$$

Putting u and v in the Equation (2.4), we have

$$af'(y) + bf'^2(y) - bf'(y)f(y) = (1-at)f'''(y) \tag{2.7}$$

and the relevant boundary conditions become

$$y = 0,\ f' = 1,\ f = 0 \tag{2.8}$$

$$y \to \infty,\ f' = 0 \tag{2.9}$$

Boundary conditions suggest that the velocity function f may be of the form $f'(y) = e^{-ry}$
where r is unknown to be determined. Thus

$$v = -\frac{b}{r(1-at)} e^{-ry}$$

and the Equation (2.7) gives $r = \sqrt{\dfrac{a+b}{1-at}}$. Therefore, we have the velocity components as follows:

$$u = \frac{bx}{1-at} \exp\left\{-\left(\sqrt{\frac{a+b}{1-at}}\right)y\right\}$$

and

$$v = -\frac{b}{\sqrt{(1-at)(a+b)}}\left[1 - \exp\left(\sqrt{\frac{a+b}{1-at}}\right)y\right] \tag{2.10}$$

3. Skin Friction

The wall shear stress at the stretching plate is given by

$$\tau_w = -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$\tau_w = \frac{\mu b x}{1-at}\sqrt{\frac{a+b}{1-at}}$$

Thus, the skin friction is

$$C_f = \frac{\tau_w}{\rho U_s^2 h} = R_e^{-1}\sqrt{\frac{a+b}{1-at}} \tag{3.1}$$

4. Heat Transfer Problem

In absence of viscous dissipation and heat generation, the energy equation for two dimensional heat flow is given b

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{4.1}$$

subject to boundary conditions

$$\begin{aligned} y = 0, T = T_P \\ y \to \infty, T = T_\infty \end{aligned} \tag{4.2}$$

where T_P is plate temperature, T_∞ is temperature of surrounding fluid, C_P is specific heat at constant pressure and k is thermal conductivity.

4.1. Case A: Prescribed Power Law Surface Temperature (PST)

Let the surface temperature be of the form

$$y = 0, T = T_p = T_\infty + A\left(\frac{x}{l}\right)^2$$

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

while the temperature outside the dynamic region be $y \to \infty, T = T_\infty$. Now, we define the dimensionless temperature by $\eta = ry$

For liquid metals, it has been found that the thermal conductivity varies with temperature in an approximately linear manner in the range from 0˚F to 400˚F. Therefore, we assume k as $k = k_\infty(1+\varepsilon\theta)$ where $\varepsilon = \dfrac{k_p - k_\infty}{k_\infty}$. Now, substituting u and v in the Equation (4.1) and changing the independent variable y to $\eta = ry$, we have

$$-(1-e^{-n})\theta' = \frac{1}{p_r}\left(\frac{a+b}{b}\right)\left(\theta'' + \varepsilon\left(\theta'^2 + \theta''\theta\right)\right) \tag{4.3}$$

with boundary conditions

$$\eta = 0, \theta = 1, \eta \to \infty, \theta = 0 \tag{4.4}$$

The Equation (4.3) can be rewritten as

$$\theta'' + \frac{P_r b\left(1-e^{-\eta}\right)\theta'}{\left(a+b\right)} + \varepsilon\left(\theta\theta'' + \theta'^2\right) = 0 \tag{4.5}$$

From Equation (4.5), we note that the heat transfer takes place in two parts according to $\in = 0$ and $\in \neq 0$. If $\in = 0$, then we have the main heat transfer due to constant thermal conductivity *i.e.*

$$\theta_m'' + \frac{p_r b\left(1-e^{-\eta}\right)\theta_m'}{a+b} = 0 \tag{4.6}$$

$$\theta_m(0) = 1, \theta_m \to 0 \text{ as } \eta \to \infty \tag{4.7}$$

and if $\in \neq 0$, then we get the first correction equation to main heat transfer as

$$\theta_c\theta_c'' + \theta_c'^2 = 0 \tag{4.8}$$

$$\theta_c(0) = 1, \theta_c \to 0, \text{ as } \eta \to \infty \tag{4.9}$$

The solution of the Equation (4.6) is

$$\theta_m = \frac{\displaystyle\int_\eta^\infty e^{-P_r\left(\frac{b}{a+b}\right)\left(\eta + e^{-\eta}\right)}\mathrm{d}\eta}{\displaystyle\int_0^\infty e^{-P_r\left(\frac{b}{a+b}\right)\left(\eta + e^{-\eta}\right)}\mathrm{d}\eta}$$

$$= \frac{\left(\dfrac{a+b}{P_r(1-at)}\right)^{P_r\left(\frac{1-at}{a+b}\right)}\gamma\left(P_r\left(\dfrac{b}{a+b}\right), P_r\left(\dfrac{b}{a+b}\right)e^{-\eta}\right)}{\gamma\left(P_r\left(\dfrac{b}{a+b}\right), P_r\left(\dfrac{b}{a+b}\right)\right)}$$

where

$$\gamma(x,\alpha) = \int_0^\alpha e^{-t}t^{x-1}\mathrm{d}t$$

is incomplete gamma function

Equation (4.8) is a non linear differential equation of order two. Let the solution of this equation be of the form:

$$\theta_c(\eta) = \eta^\alpha$$

Putting this solution in Equation (4.8) we have

$$2\alpha^2 - \alpha = 0 \tag{4.10}$$

The roots of this equation are 0 and 1/2. Therefore

$$\theta_c(\eta) = 1 - \sqrt{\eta} \tag{4.11}$$

The solution (4.11) of the Equation (4.8) does not satisfy the condition $\theta_c \to 0$ as $\eta \to \infty$. This condition is met only for $\eta \to 1$. Therefore, the heat transfer in case $\in \neq 0$ takes place within the dynamic region $0 \leq \eta \leq 1$.

4.2. Nusselt Number

The coefficient of convective heat transfer is given by

$$q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=0} \qquad (*)$$

Therefore the Nusselt number is (see **Table 2**):

$$Nu = \frac{q_w}{k\left(T_p - T_\infty\right)}$$

$$Nu = -\frac{k}{k\left(T_p - T_\infty\right)}\left(\frac{\partial T}{\partial y}\right)_{y=0}$$

$$= \left(\sqrt{\frac{a+b}{1-at}}\right)\frac{\exp\left(\frac{p_r(1-at)}{a+b}\right)}{\gamma\left(p_r\left(\frac{1-at}{a+b}\right), p_r\left(\frac{1-at}{a+b}\right)\right)} \qquad (4.12)$$

4.3. Case B: Prescribed Power Law Surface Heat Flux (PHF Case)

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

$$-k\frac{\partial T}{\partial y} = D\left(\frac{x}{l}\right)^2 \quad \text{at} \quad y = 0 \qquad (4.13)$$

$$T \to T_\infty, \quad \text{as} \quad y \to \infty \qquad (4.14)$$

where D is a constant, k is the thermal conductivity. Now we define dimensionless temperature $g(\eta)$ by

$$g(\eta) = \frac{T - T_\infty}{T_p - T_\infty}, \qquad (4.15)$$

where

$$T_p - T_\infty = \frac{D}{kr}\left(\frac{x}{l}\right)^2 \quad \text{when} \quad g'(0) = -1$$

where $\eta = ry$

Writing the Equation (4.2) in terms of $g(\eta)$, we get the following differential equation

$$g''(\eta) + \frac{P_r b\left(1-e^{-\eta}\right)}{a+b} + g'(\eta) + \varepsilon\left(gg'' + g'^2\right) = 0 \quad (4.16)$$

together with boundary conditions:

$$g' = -1 \text{ at } \eta = 0$$
$$g \to 0 \text{ as } \eta \to \infty \qquad (4.17)$$

Equating the terms independent of and the terms involving from Equation (4.16), we get the following two boundary value problems:

$$g_m''(\eta) + \frac{P_r b\left(1-e^{-\eta}\right)}{a+b} g_m'(\eta) = 0 \qquad (4.18)$$

and

$$g_c(\eta)g_c''(\eta) + g_c'^2 = 0 \qquad (4.19)$$

where the nomenclature g_m is main heat transfer when thermal conductivity is constant and g_c is correction to the heat flow due to variation in thermal conductivity in PHF case. The solution of the Equation (4.18) together with the boundary conditions (4.18) is

$$g_m(\eta) = e^{P_r\left(\frac{a}{a+b}\right)}\int_\eta^\infty \left(\frac{a}{a+b}\right)\left(\eta + e^{-\eta}\right)\mathrm{d}\eta \qquad (4.20)$$

The general solution of the Equation (4.19) is

$$g_c(\eta) = A + B\sqrt{1-\eta} \qquad (4.21)$$

where we again observe that the dynamic region for this temperature field is $0 \le \eta \le 1$. Hence, the boundary conditions (4.17) have been modified as

$$g_c(0) = -1, \text{ and } g_c \to 0 \text{ as } \eta \to 1 \qquad (4.22)$$

Using boundary conditions (4.22), the solution (4.19) becomes

$$g_v = 2\sqrt{1-\eta}$$

4.4. Nusselt Number (See Table 3)

Recalling (*), we have

$$q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=0}$$

$$Nu = -\frac{k}{k\left(T_p - T_\infty\right)}\left(\frac{\partial T}{\partial y}\right)_{y=0}$$

$$= \sqrt{\frac{a+b}{1-at}}e^{\frac{2P_r(1-at)}{a+b}}$$

5. Discussion and Results

The problem of unsteady boundary layer flow of viscous

Table 2. Trend of Nusselt number.

t	Nu for $P_r = 1.54$	Nu for $P_r = 2.15$	Nu for $P_r = 5.10$	Nu for $P_r = 9.42$
0	26.356	95.389	4.574×10^4	0.343×10^9
0.2	19.976	64.026	1.667×10^4	0.522×10^8
0.4	15.332	43.062	6.012×10^3	0.795×10^7
0.6	11.828	29.255	2.234×10^3	116.283×10^4
0.8	9.212	20.043	834.364	185.922×10^3
1.0	7.271	13.906	312.276	28.727×10^3

Table 3. Trend of Nusselt number.

t	Nu for $P_r = 1.54$	Nu for $P_r = 2.15$	Nu for $P_r = 5.10$	Nu for $P_r = 9.42$
0	21.758	73.7	2.69×10^4	1.521×10^8
0.2	16.856	50.536	1.023×10^4	2.473×10^7
0.4	13.139	34.868	3.911×10^3	3.928×10^6
0.6	10.323	24.248	1.508×10^3	6.382×10^5
0.8	8.194	17.037	587.228	1.048×10^5
1.0	6.597	12.141	231.962	1.744×10^4

incompressible fluid overstretching plate has been analyzed. The velocity field has been obtained by similarity transformation method. Later, the heat flow problem has been studied by considering PST and PHF cases. We summarize the results as in **Figure 1** to **Figure 6**.

Figure 1 shows that horizontal component of velocity u. It increases as time progresses within the dynamical region [0, 1]. We also see that u is maximum in the immediate neighborhood of stretching plate and it starts decreasing as $y \to 1$. In fully developed flow, as time goes on progressing, the velocity progresses too.

Figure 2 is a graph of v versus y for different instant of time. The vertical component v is almost constant within [0, 1] and later it starts increasing. v progresses as we march away from the slit and it also increases as time progresses.

Figure 3 is to study the variation of mean temperature field θ_m with respect to Prandtl number P_r. We see that as P_r increases, θ_m decreases within dynamical region [0,1] in PST case. As $P_r = \dfrac{ul}{v}$ decreases, *i.e.* kinematic viscosity v increases in turn viscosity of fluid increases. In case of more viscosity, generally flow of heat becomes slow. It is supported by our study.

Figure 4 is expressing the trend of temperature field θ_c due to variable thermal conductivity. We see that the contribution of this temperature is more near the moving plate than as we go away from the plate in PST case. θ_c
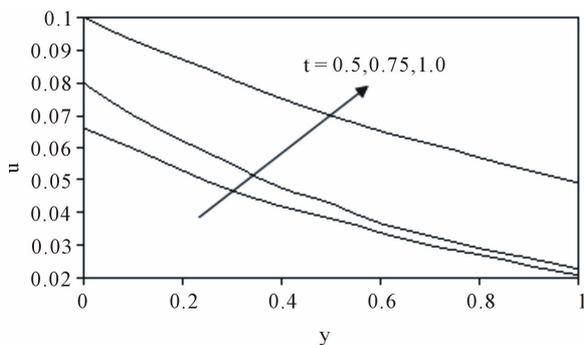
Figure 1. Velocity field at different instant of time.
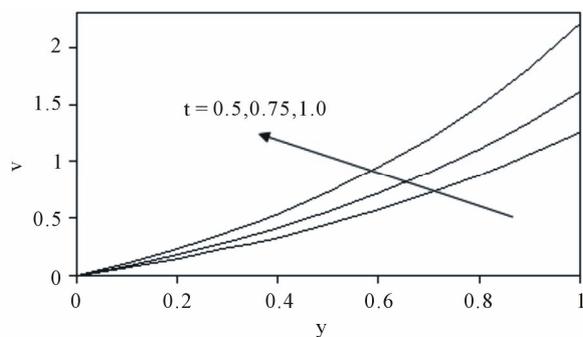
Figure 2. Velocity component *v* at different instant of time.
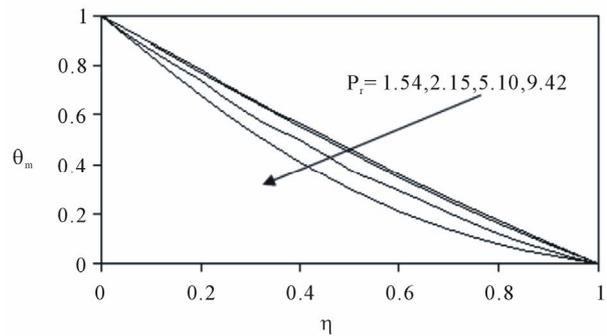
Figure 3. Mean temperature field for different values of Prandtl number *P_r* in PST case.
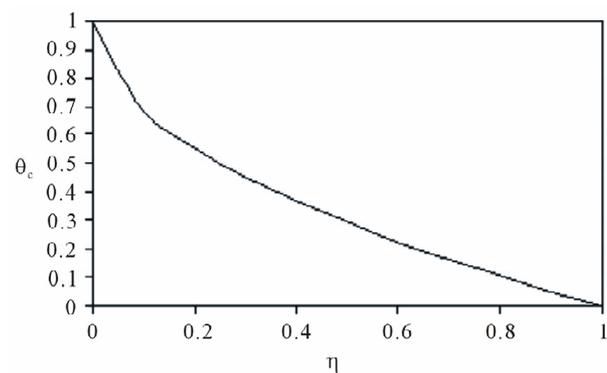
Figure 4. Temperature distribution due to variation in thermal conductivity.
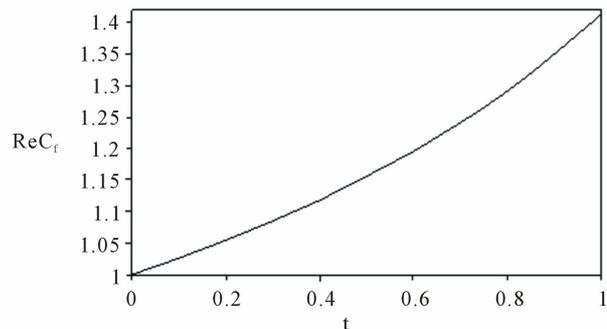
Figure 5. Skin friction with respect to time *t*.
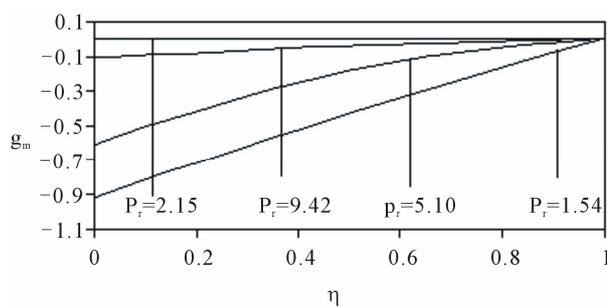
Figure 6. Temperature field for different values of Prandtl number in PHF case.

is independent of Prandtl number P_r.

Figure 5 is the graph of $\mathrm{Re}C_f$ versus time. We see that as time progresses the skin friction increases .We mean that as time progresses the velocity increases, in turn skin friction increases.

Figure 6 is temperature field in PHF case. We see that it approaches to zero asymptotically.

We see the g_m for $P_r = 5.10$ of liquid oxygen at 56˚K, $P_r = 2.15$ of para-hydrogen at 14˚K and $P_r = 1.54$ of liquid ammonia at 10˚C. It has been observed that g_m increases absolutely as P_r increases, but for $P_r = 9.42$ of water at 10˚C, g_m behaves in a different way due to its density.

Nusselt number in PST case is given by the Equation (4.12) where we observe referring **Table 2** that it depends on Prandtl number and time t as well. From **Table 1** we find that as Prandtl number increases the Nusselt number also increases but Nusselt number decreases as time increases.

Referring **Table 3** for PHF case, we see the same pattern as in PST case from **Table 2**.

We have not got Prandtl number from the temperature field due to variation in thermal conductivity.

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