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UNSTEADY FREE-CONVECTION IN BINARY MIXTURE OF A BOUNDARY LAYER FLOW PAST A VERTICAL POROUS PLATE WITH RADIATIVE HEAT TRANSFER

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Abstract: The combined free convection dynamic boundary layer and thermal radiation boundary layer along a semi-infinite vertical porous plate with mass transfer has been analyzed. The chemical reaction for a very simple model of a binary reaction with Arrhenius activation energy is incorporated into the analysis. The fluid is considered to be gray, absorbing-emitting. Under such conditions, the coupled and unsteady non-linear momentum, energy and concentration equations of the combined layers are then made similar by introducing a time dependent length scale and by the usual method of similarity transformation. The similarity equations are then solved numerically by the method of superposition. The resulting velocity and t emperature distributions are shown graphically for different values of the parameters entering into the problem. The numerical values of the skin friction coefficient (τ_W) and the Nusselt number (N_u) are calculated and presented in a tabular form.

Key words: Boundary layer; Heat transfer; Chemical reaction; Binary mixture; Arrhenius activation energy

Introduction

Heat transfer by natural convection in laminar boundary layer flows has been analyzed extensively for semi-infinite vertical, horizontal and inclined orientations (Abramowitz, 1972; Alabraba, 1992; Bestman, 1990 and Bratis, 1973). On the other hand, heat transfer by simultaneous natural convection and thermal radiation in a participating fluid has not received much attention. Whereas, thermal radiation can play a significant role in the overall surface heat transfer when the convection heat transfer is small particularly in free convection problems involving absorbing-emitting fluids.

In recent times, the problem of radiative transfer in a vertical channel has been studied for the re-entry problem. As an initiator of this problem of radiative transfer in a vertical surface, Goody (1956) considered a neutral fluid. Cess (1966), however, considered an absorbing-emitting gray fluid with a black vertical plate. His solutions were based on

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perturbation technique and were applicable for small values of the conduction-radiation interaction parameter. Bratis and Novotny (1973), on the other hand, made the non-gray analysis employing limiting forms to approximate the band profile. Novotny et al. (1974) then studied the same problem employing the method of local non-similarity and the continuous correlation of Tien and Lowder (1974) to account the band absorption.

Recently, in light of the work of Cess (1966), the study of the interaction of natural convection with thermal radiation in laminar boundary layer with isothermal horizontal surface in a gray-gas was made by Ali et al.(1984). Following Ali et al. (1984), Mansour (1990) studied the interaction of mixed convection with thermal radiation in laminar boundary layer flow over a horizontal, continuous moving sheets with suction and injection. He then studied the interaction of thermal radiation at a semi-infinite plate longitudially streamlined by viscoelastic fluid. On the other hand, in areas applicable in geothermal and well reservoir engineering etc., there is usually chemical reaction with finite Arrhenius activation energy. In this light, Bestman (1990) made a study of a laminar natural convection boundary layer in porous medium making a very simple model of a binary reaction with Arrhenius activation energy. The re-entry problem discussed above when combined with chemical reaction processes a challenge for the engineering community. Afterwards a mathematical approach to this problem in case of a steady flow has been made by Alabraba *et al.* (1992). They, of course, considered the problem of free convection interaction with thermal radiation in a hydromagnetic boundary layer taking into account the binary chemical reaction and the less attended Soret and Dufour effects.

The present investigation considers the above problem of unsteady free convection interaction with thermal radiation of an absorbing-emitting fluid along a vertical plate with variable suction. The investigation is based on similarity analysis by employing a time-dependent similarity parameter. The similarity solutions are then obtained numerically for very small values of the conduction radiation parameter and for a constant chemical reaction rate, which are of practical interest from physical point of view.

Mathematical Formulation

We consider a viscous incompressible flow with a combined free convection dynamic boundary layer along a semi-infinite vertical permeable wall. The x-axis is taken along the plate in the flow direction and y-axis is perpendicular to the plate. The gravitation g acts in the negative direction of x. It is assumed that the plate is infinite in extent and hence all physical quantities depend on y and time t and so the derivatives of all these quantities with respect to x become zero. We now consider that the density change is important only in the gravitational term of the equation of motion. This is due to the fact that the acceleration resulting from the variation of density in the external force is quite large compared to the accelerations, for example, due to the inertial term in the equations of motion. This approximation is known as Boussinesq's approximation. Thus within the frame work of these assumptions the equations relevant to the problem are

$$\frac{\partial v}{\partial y} = 0\,, \tag{1}$$

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) + g\beta^*(C - C_\infty)\,, \tag{2}$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{\alpha}{\kappa}\frac{\partial q_r}{\partial y}\,, \tag{3}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - \kappa_r^{\,2}(T - T_\infty)^\omega \exp[-\frac{E}{\kappa_\beta (T - T_\infty)}](C - C_\infty)\,, \tag{4}$$

where (u, v) is the velocity vector, T and C are, respectively the temperature and concentration of the fluid, T_∞ and C_∞ are respectively the temperature and concentration of the fluid in the static flow far away from the boundary, ν is the kinematic co-efficient of viscosity, α is the thermal conductivity, κ is the heat diffusivity temperature, β is the coefficient volume for thermal expansion, β^* is the coefficient volume expansion for concentration, D is the coefficient of the mass difusivity, $\kappa_r^{\,2}$ is the chemical reaction rate constant and $(T - T_\infty)^\omega \exp[-\frac{E}{\kappa_\beta (T - T_\infty)}]$ is the Arrhenius function where E is the activation energy, κ_β is the Boltzmann constant and ω is a constant exponent.

The radiative heat flux term is simplified by the use of the Rosseland approximation (c.f. Sparrow and Cess (1978) as:

$$q_r = -\frac{4s}{3K}\frac{\partial T^4}{\partial y} \tag{5}$$

where, s and K are the Stefan-Boltzmann constant and the mean absorption coefficient respectively. Since the plate is considered to be porous, there is a suction at the plate. Taking the velocity suction as $v(t)$, we have the boundary condition for our problem as:

$$\left.\begin{array}{ll} u = 0,\quad v = v(t),\quad T = T_\omega,\quad C = C_\omega & at \quad y = 0 \\ u \to 0,\quad v \to 0,\quad T \to T_\infty,\quad C \to C_\infty & as \quad y \to \infty \end{array}\right\}. \tag{6}$$

Our aim is to obtain a similarity solution to the problem considered. We thus introduce a similarity parameter

$$\sigma = \sigma(t) \tag{7}$$

where, σ is the length scale.

The continuity equation (1) can then be satisfied in terms of this length scale σ as

$$v = -\frac{\nu}{\sigma}v_0 \tag{8}$$

where v_0 is a dimensionless suction parameter.

Now to solve the system of equations (2), (3) and (4), under the boundary conditions (6), we introduce similarity transformations as

$$\left.\begin{aligned} \eta &= \frac{y}{\sigma} \\ u &= U_0 f(\eta) \\ \theta(\eta) &= \frac{T - T_\infty}{T_\omega - T_\infty} \\ \phi(\eta) &= \frac{C - C_\infty}{C_\omega - C_\infty} \end{aligned}\right\} \tag{9}$$

where, U_0 is a constant uniform velocity.

Now introducing the relations (7) – (9) in the equations (2), (3) and (4) respectively, we obtain the following three locally similar ordinary differential equations

$$-\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}\eta f^{/} - v_0 f^{/} = f^{//} + G_r\theta + G_m\phi, \tag{10}$$

$$-\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}\eta\theta^{/} - v_0\theta^{/} = \frac{1}{P_r}\theta^{//} + \frac{R}{P_r}[3(C_T + \theta)^2\theta^{/2} + (C_T + \theta)^3\theta^{//}], \tag{11}$$

and

$$-\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}\eta\phi^{/} - v_0\phi^{/} = \frac{1}{S_c}\phi^{//} - \kappa_R\theta^{\omega} e^{-\left(\frac{E_c}{\theta}\right)}\phi \tag{12}$$

where, $\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}$ is a dimensionless quantity,

$G_r = \frac{g\beta(T_\omega - T_\infty)\sigma^2}{\nu U_0}$ the Grashof number,

$G_r = \frac{g\beta^*(C_\omega - C_\infty)\sigma^2}{\nu U_0}$ the modified Grashof number,

$P_r = \frac{\nu}{\alpha}$ the Prandtl number,

$\kappa_R = \frac{\sigma^2\kappa_r^2}{\nu}(T_\omega - T_\infty)^{\omega}$ the dimensionless chemical reaction rate constant, coefficient.

$S_c = \frac{\nu}{D}$ the Schmidt number,

$E_c = \frac{E}{\kappa_\beta (T_\omega - T_\infty)}$ the activation energy and

$R = \frac{16s}{3K\kappa}(T_\omega - T_\infty)^3$ the conduction radiation parameter.

The equations (10) to (12) are similar except the dimensionless quantity $\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}$ where time t appears explicitly. Thus the similarity condition requires that this quantity $\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t}$ in the equations (10) – (12) must be a constant quantity. Hence following the work of Sattar and Hossain (1992), one can try a class of solutions of the equations (10) – (12) by assuming that

$$\frac{\sigma}{\nu}\frac{\partial\sigma}{\partial t} = C \text{ (a constant)} \tag{13}$$

Now integrating (13) one obtains

$$\sigma = \sqrt{2C\nu t} \tag{14}$$

where, the constant of integration is determined through the condition that $\sigma = 0$ when $t = 0$. Thus it appears from (14) that, by making a realistic choice of C to be equal to 2 in (13) the length scale σ becomes equal to $\sigma = \sqrt{2\nu t}$ which exactly corresponds to the usual scaling factor considered for various non steady boundary layer flows (Schlichting, 1968). Since σ a scaling factor as well as similarity parameter, any value of C in (13) would not change the nature of the solution except that the scale would be different. Finally, introducing (13) with $C = 2$ in the equations (10) – (12), we respectively have the following dimensionless ordinary differential equations:

$$f^{//} + 2\xi f^{/} + G_r\theta + G_m\phi = 0 \tag{15}$$

$$\theta^{//} + 2P_r\xi\theta^{/} = -R[3\{(C_T+\theta)^2\theta^{/2} + (C_T+\theta)^3\theta^{//}] \tag{16}$$

$$\phi^{//} + 2S_c\xi\phi^{/} - S_c\kappa_R\theta^{\omega}e^{-\left(\frac{E_c}{\theta}\right)}\phi = 0 \tag{17}$$

where $\xi = \eta + \frac{v_0}{2}$.

Corresponding to the equations (15) to (17), the boundary conditions (6) now transform to

$$\left.\begin{aligned} f &= 0, \quad \theta = 1, \quad \phi = 1 \quad at \quad \eta = 0, \\ f &= 0, \quad \theta = 0, \quad \phi = 0 \quad as \quad \eta \to \infty \end{aligned}\right\} \tag{18}$$

Our physical problem is now reduced to a set of three ordinary differential equations, the solutions of which are now sought subject to the boundary conditions (18).

Solutions

For mathematical brevity we will consider the case for which $\omega = E_c = 0$ and hence the concentration equation (17) becomes

$$\phi'' + 2S_c\xi\phi' - S_c\kappa_R\phi = 0 . \tag{19}$$

According to Abramowiz and Stegun (1972), the general solution of the equation (19) is of the form:

$$\phi(z) = \frac{1}{Hh_n\left(\sqrt{\frac{S_c}{2}}v_0\right)} Hh_n(\sqrt{2}z) \tag{20}$$

where, $\sqrt{S_c}\xi = z$ and the function $Hh_n(rx)$ is defined as $Hh_n(rx) = \int_{rx}^{\infty} \frac{(s - rx)}{n} \exp(-\frac{s^2}{2})ds$. Other properties of the function $Hh_n(rx)$ are defined by Jeffrys and Jeffrys (1972).

To solve the equations (15) and (16) which are coupled non-linear, we take a series expansion of the function f and θ as:

$$\left.\begin{aligned} f &= f_0 + Rf_1 + R^2 f_2 + \dots \\ \theta &= \theta_0 + R\theta_1 + R^2\theta_2 + \dots \end{aligned}\right\} . \tag{21}$$

Now inserting (20) in the equations (15) and (16) and then equating the corresponding coefficients of the various powers of R (up to 2), the following set of equations are obtained

$$f_0'' + 2\xi f_0' + G_r\theta_0 + G_m\phi = 0 , \tag{22}$$

$$f_1'' + 2\xi f_1' + G_r\theta_1 = 0 , \tag{23}$$

$$\theta_0'' + 2P_r\xi\theta_0' = 0 , \tag{24}$$

$$\theta_1'' + 2P_r\xi\theta_1' = -R[3(C_T + \theta_0)^2\theta_0'^2 + (C_T + \theta_0)^3\theta_0''] . \tag{25}$$

The boundary conditions corresponding to the equations (22) to (25) are

$$\left.\begin{aligned} &f_0 = 0, \quad f_1 = 0, \quad \theta_0 = 1, \quad \theta_1 = 0 \quad at \quad \eta = 0 \\ &f_0 = 0, \quad f_1 = 0, \quad \theta_0 = 0, \quad \theta_0 = 0 \quad as \quad \eta \to \infty \end{aligned}\right\} . \tag{26}$$

The equation (24) is very simple. It’s solution is obtained analytically as:

$$\theta_0(z) = \frac{1}{erfc\left(v_0 \frac{\sqrt{P_r}}{2}\right)} erfc(z) \tag{27}$$

In the above equation the function $erfc(z)$ is defined as $erfc(z) = 1 - erf(z)$,

where, $erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt.$

Now substituting (27) in (22), (23) and (25), the solutions of equations (22), (23) and (25) are obtained by the method of superposition (Na, 1979). This method is used to reduce the boundary value problem to an initial value problem that can easily be integrated out without any iteration, by an initial value solver. Thus to reduce equations (22), (23) and (25) to an initial value problem the function $f_0(\eta), f_1(\eta)$ and $\theta_0(\eta)$ are respectively decomposed to

$$\left.\begin{aligned} f_0(\eta) &= f_{01}(\eta) + \mu f_{02}(\eta) + \varepsilon f_{03}(\eta) + \delta f_{04}(\eta) \\ f_1(\eta) &= f_{11}(\eta) + \mu f_{12}(\eta) + \varepsilon f_{13}(\eta) + \delta f_{14}(\eta) \\ \theta_1(\eta) &= \theta_{11}(\eta) + \mu\theta_{12}(\eta) + \varepsilon\theta_{13}(\eta) + \delta\theta_{14}(\eta) \end{aligned}\right\} \tag{28}$$

where, μ, ε and δ are constants, the physical significance of which is obtained later. The initial values of the decomposed functions $f_{01}(\eta), f_{02}(\eta), f_{03}(\eta), f_{04}(\eta), f_{11}(\eta), \ldots$ etc. are now obtained through the boundary conditions (26) as

$$\left.\begin{aligned} & f_{01}(\eta) = 0,\ f_{02}(\eta) = 0,\ f_{03}(\eta) = 0,\ f_{04}(\eta) = 0 \\ & f_{11}(\eta) = 0,\ f_{12}(\eta) = 0,\ f_{13}(\eta) = 0,\ f_{14}(\eta) = 0 \\ & \theta_{11}(\eta) = 0, \theta_{12}(\eta) = 0, \theta_{13}(\eta) = 0, \theta_{14}(\eta) = 1 \end{aligned}\right\} \tag{29}$$

where, $\theta_1(0)$ is taken to be equal to δ for analytic simplicity. Again, as $\eta \to \infty$, applying the boundary conditions (26) in (28) one has

$$\left.\begin{aligned} \mu &= -\frac{f_{01}(f_{13}\theta_{14} - f_{14}\theta_{13}) + f_{11}(f_{04}\theta_{13} - f_{03}\theta_{14}) + \theta_{11}(f_{14}f_{03} - f_{04}f_{13})}{f_{02}(f_{13}\theta_{14} - f_{14}\theta_{13}) + f_{03}(f_{14}\theta_{12} - f_{12}\theta_{14}) + f_{04}(f_{12}\theta_{13} - f_{13}\theta_{12})} \\ \varepsilon &= -\frac{f_{01}(f_{14}\theta_{12} - f_{12}\theta_{14}) + f_{11}(f_{02}\theta_{14} - f_{04}\theta_{12}) + \theta_{11}(f_{12}f_{04} - f_{02}f_{14})}{f_{02}(f_{13}\theta_{14} - f_{14}\theta_{13}) + f_{03}(f_{14}\theta_{12} - f_{12}\theta_{14}) + f_{04}(f_{12}\theta_{13} - f_{13}\theta_{12})} \\ \delta &= -\frac{f_{01}(f_{12}\theta_{13} - f_{13}\theta_{12}) + f_{11}(f_{03}\theta_{12} - f_{02}\theta_{13}) + \theta_{11}(f_{13}f_{02} - f_{03}f_{12})}{f_{02}(f_{13}\theta_{14} - f_{14}\theta_{13}) + f_{03}(f_{14}\theta_{12} - f_{12}\theta_{14}) + f_{04}(f_{12}\theta_{13} - f_{13}\theta_{12})} \end{aligned}\right] \tag{30}$$

In (30) all the functional values are obtained at $\eta \to \infty$. Now from (28) we have

$$\frac{\partial f_0(\eta)}{\partial \eta} = \frac{\partial f_{01}(\eta)}{\partial \eta} + \mu \frac{\partial f_{02}(\eta)}{\partial \eta} + \varepsilon \frac{\partial f_{03}(\eta)}{\partial \eta} + \delta \frac{\partial f_{04}(\eta)}{\partial \eta}$$

$$\frac{\partial f_1(\eta)}{\partial \eta} = \frac{\partial f_{11}(\eta)}{\partial \eta} + \mu \frac{\partial f_{12}(\eta)}{\partial \eta} + \varepsilon \frac{\partial f_{13}(\eta)}{\partial \eta} + \delta \frac{\partial f_{14}(\eta)}{\partial \eta}$$

$$\frac{\partial \theta_1(\eta)}{\partial \eta} = \frac{\partial \theta_{11}(\eta)}{\partial \eta} + \mu \frac{\partial \theta_{12}(\eta)}{\partial \eta} + \varepsilon \frac{\partial \theta_{13}(\eta)}{\partial \eta} + \delta \frac{\partial \theta_{14}(\eta)}{\partial \eta}$$

Then by setting the missing slopes $\frac{\partial f_0(0)}{\partial \eta}$ and $\frac{\partial f_1(0)}{\partial \eta}$ as $\frac{\partial f_0(0)}{\partial \eta} = \mu$ and $\frac{\partial f_1(0)}{\partial \eta} = \varepsilon$. The initial conditions for the slopes of the decomposed functions are obtained easily. The well known Runge-Kutta Merson Integration Scheme (MIS) has been used as an initial value solver to integrate the above mentioned equations and to obtain converged solution. The solutions, thus obtained, are displayed in Figs. 1–12. The effects of various parameters on the shearing stress (τ_ω) and the Nusselt number (N_u) are obtained from the process of numerical calculations and are shown in tabular form in Table 1.

Table 1. Numerical values of the dimensionless local wall shearing stress τ_ω and the Nusselt number N_u for $G_m = 0.6$ and $S_c = 0.2$

κ_r	P_r	G_r	C_r	R	v_0	*Shearing stress* τ_ω	*Nusselt No.* N_u
0	0.71	10	1.0	0.1	0.5	5.899745	0.4520123
1	0.71	10	1.0	0.1	0.5	6.076708	0.4520123
2	0.71	10	1.0	0.1	0.5	6.944033	0.4520123
2	1.00	10	1.0	0.1	0.5	6.272170	0.5450249
2	7.00	10	1.0	0.1	0.5	3.511248	1.6936360
2	0.71	08	1.0	0.1	0.5	5.927558	0.4520188
2	0.71	05	1.0	0.1	0.5	4.402849	0.4520188
2	0.71	10	0.6	0.1	0.5	6.460076	0.7976857
2	0.71	10	0.2	0.1	0.5	6.194652	1.0158540
2	0.71	10	1.0	0.2	0.5	7.842276	0.2836929
2	0.71	10	1.0	0.0	0.5	6.046890	1.1877170
2	0.71	10	1.0	0.1	1.0	8.519076	0.4915183
2	0.71	10	1.0	0.1	1.5	11.38190	0.5334170

Results and Discussion

In the present paper, we have attempted to solve the flow of the combined free convection dynamic boundary layer and thermal radiation boundary layer along a semi-infinite vertical porous plate with mass transfer. In the mass transfer equation, the term due to chemical reaction has also been incorporated. From the mathematical point of view the chemical reaction, when introduced in a flow, the dynamic equations become very complex and highly non-linear. But making a very simple model of a binary reaction with Arrhenius activation energy, one can reasonably tackle the mathematics of the problem. In this paper, we have further simplified the problem by taking a constant chemical reaction rate with zero activation energy.

Our present work is in fact an extension to the work of Sattar and Kalim (1996) who obtained the solutions without mass transfer effect as well as the chemical reaction. The results of the velocity and temperature distributions of our problem under some limitations are shown in Figs. 1–12. The corresponding results for the skin friction and the Nusselt number are shown in tabular form in Table 1.

The effects of the chemical reaction rate κ_R on the velocity field are shown in Fig. 1. It appears from Fig. 1 that velocity increases slightly at a moderate value $(\kappa_r = 1)$ of the chemical reaction rate in comparism with the velocity without any reaction rate. However, if the reaction is increased further $(\kappa_r = 2)$, it is observed that the velocity tends to decrease. Form Fig. 2, it is apparent that the chemical reaction rate, under simplifications considered, practically has no effect on the temperature field. In Fig. 3, the effects of the Prandtl number P_r are shown on the velocity field. Fig. 3 shows that velocity decreases at a particular point of the combined boundary layer with the increase of the Prandtl number P_r . The same effect of Prandtl number is also observed from Fig. 4 in the case of temperature field. In Figs. 5 and 6, the effect of the Grashof number G_r on the velocity and temperature fields are shown respectively. Since the Grashof number G_r does not enter into the energy equation directly, its effects are only through the velocity field. Fig. 5 however shows that velocity increases with the increase of the Grashof number G_r which is usually expected. In Fig. 7, the effects of the temperature difference parameter C_T on the velocity field reveals that the velocity increases with the increase of the temperature difference parameter C_T . The same effects are also observed in case of the temperature field in Fig. 8.

It was earlier mentioned that our problem has been solved for small values of the radiation conduction parameter R . In Fig. 9, the curve for $R = 0$ essentially represents the velocity profile for pure natural convection. As the interaction of thermal radiation intensifies (increasing R), the velocity increases with an accompanying increase in the velocity gradient at the wall (Table 1). The same effects of the radiation conduction parameter R on the temperature field are also observed as seen in Fig. 10. The effects of the suction parameter v_0 on the velocity and temperature fields are observed from the Figs. 11 and 12 respectively. Fig. 11 shows that velocity decreases with the increase of the suction parameter which is usually expected because suction is known to be one of the best methods of reducing the velocity in a boundary layer problem. From Fig. 12, the same effect is also observed in case of the temperature field.

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Finally, the effects of various parameters on the shearing stress (τ_{ω}) and the Nusselt number (N_u) are shown in tabular form in Table 1. These effects are clearly discerned from this table and hence their discussions are not presented for brevity.

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