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THERMAL RADIATION EFFECTS ON FLOW PAST AN IMPULSIVELY STARTED VERTICAL MOVING PLATE WITH UNIFORM HEAT AND MASS FLUX

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ABSRACT: In this paper the thermal radiation effects on the free convection flow of a viscous incompressible fluid past an impulsively started vertical plate with uniform heat and mass flux has been analyzed. The fluid considered here is a grey absorbing emitting but a non scattering medium and Rosseland approximation is used to describe the radiative heat flux in the energy equation. The dimensionless governing equations are solved by using Laplace transform technique. Numerical results for the velocity, temperature and concentration are shown graphically.

Keywords:Heat and Mass transfer, Radiation, Schmidt number, Radiation, Grashof Number and modified Grashof number

I. INTRODUCTION

The analysis of natural convection heat and mass transfer near a moving vertical plate has received much attention in recent times due to its wide application in engineering and technological processes. There are applications of interest in which combined heat and mass transfer by natural convection occurs between a moving material and the ambient medium, such as the design and operation of chemical processing equipment, design of heat exchangers, transpiration cooling of a surface, chemical vapor deposition of solid layers, nuclear reactors, and many manufacturing processes like hot rolling, hot extrusion, wire drawing, continuous casting, and fiber drawing. Soundalgekar [17] studied the effects of mass transfer on the free convection flow past an impulsively started infinite vertical plate and presented an exact solution by the Laplace transform method. Soundalgekar and his co-researchers [18] investigated the effects of simultaneous heat and mass transfer on free convection flow past an infinite vertical plate under different physical situations. Das et al. [5] considered the mass transfer effects on the flow past an impulsively started infinite isothermal vertical plate with constant mass flux and chemical reaction. Muthucumaraswamy and Ganesan [10] considered the problem of unsteady flow past an impulsively started isothermal vertical plate with mass transfer by an implicit finite difference method. Muthucumaraswamy and Ganesan [11,12] solved the problem of unsteady flow past an impulsively started vertical plate with uniform heat and mass flux and variable temperature and mass flux respectively.

In the context of space technology and in processes involving high temperatures the effects of radiation are of vital importance. Recent developments in hypersonic flights, missile reentry, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal radiation as a mode of energy transfer, and emphasize the need for improved understanding of radiative transfer in these processes. The interaction of radiation with laminar free convection heat transfer from a vertical plate was investigated by Cess [2] for an absorbing, emitting fluid in the optically thick region, using the singular perturbation technique. Arpaci [1] considered a similar problem in both the optically thin and optically thick regions and used the approximate integral technique and first-order profiles to solve the energy equation. Cheng and Ozisik [3] considered a related problem for an absorbing, emitting and isotropically scattering fluid, and treated the radiation part of the problem exactly with the normal-mode expansion technique. Mansour [13] studied the radiative and free convections effects on the oscillatory flow past a vertical plate. Hossain and Takhar [7] studied the radiation effects on mixed convection along a vertical plate with uniform surface temperature using Keller Box finite difference method. In all these papers the flow is considered to be steady. Raptis and Perdikis [16] studied the effects of thermal radiation and free convective flow past moving plate. Das et al. [6] have analyzed the radiation effects on flow past an impulsively started infinite isothermal vertical plate. The governing equations were solved by the Laplace transform technique. Chamkha et al. [4] have studied the radiation effects on free convection flow past a semi-infinite vertical plate with mass transfer. Loganathan and Ganesan [9] considered the effect of radiation on the free convection flow past an impulsively started vertical plate in the presence of mass transfer. A 2-dimensional analysis of heat and mass transfer inside a rectangular moist object under the drying process was presented by Kaya et al. [8] using an implicit finite difference method. Prasad et al. [15] examined the radiation and mass transfer effects on the unsteady 2-dimensional free convection flow of a viscous incompressible fluid past an

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impulsively started infinite vertical plate. Recently, Narahari and Dutta [14] presented a theoretical solution to the free convection flow of a viscous incompressible fluid past an infinite vertical moving plate subject to a ramped surface temperature with simultaneous mass transfer using the Laplace transform technique.

The aim of the present chapter is to study unsteady, laminar, simultaneous free convective heat and mass transfer flow along an impulsively started plate in the presence of thermal radiation effects. The solution of the problem is obtained by using Laplace transform technique.

II. FORMULATION OF THE PROBLEM

An unsteady free convection and mass transfer flow of a viscous incompressible and electrically conducting radiating fluid past an impulsively started semi-infinite non-conducting vertical plate with uniform and mass flux is considered. It is assumed that the diffusing species and the fluid on the plate an arbitrary point has been chosen as the origin of a Cartesian co-ordinate system with the x-axis is taken along the plate in the vertical upward direction and the y-axis is taken normal to the plate. Initially, for time $t' \le 0$, the plate and the fluid are maintained at the same constant temperature T_∞' in a stationary condition with the same species concentration C_∞'at all points. Subsequently ($t' > 0$), the plate is assumed to be accelerating with a velocity u_0 f(t) in its own plate along the x' axis instantaneously the temperature of the plate and the concentration are raised to $\frac{q}{k}$ *and* $\frac{j''}{D}$ respectively, which are here after regarded as constant. Under these assumptions, the equations that describe the physical situations are given by

$$\frac{\partial u^*}{\partial t^*} = g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) + \vartheta \frac{\partial^2 u^*}{\partial y^{*2}} \quad (1)$$

$$\rho C_p \frac{\partial T^*}{\partial t^*} = k\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{\partial q_r}{\partial y^*} \quad (2)$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} \quad (3)$$

With the following initial and boundary conditions

$$u^* = 0,\ T^* = T_\infty^*,\ \ C^* = C_\infty^* \quad \text{for all } y^* \ge 0, \text{t} \le 0$$

$$u = u_0 f(t),\ \frac{\partial T^*}{\partial y^*} = -\frac{q^*}{k},\ \frac{\partial C^*}{\partial y^*} = -\frac{q_w{}^*}{D} \quad at\ y^* = 0, \text{t} > 0$$

$$u^* \to 0,\ T^* \to T_\infty^*,\ C^* \to C_\infty^*\ as\ \ y^* \to \infty, \text{t} > 0 \quad (4)$$

By using the Rosseland diffusion approximation, the radiative heat flux is given by

$$q_r{}^* = -\frac{4\sigma^*}{3K_1{}^*}\frac{\partial T^{*4}}{\partial y^*} \quad (5)$$

It is assumed that the temperature differences within the flow are sufficiently small such that T^{*4} may be expressed as a linear function of the temperature. This is accomplished by expanding T^{*4} in a Taylor series about T_∞^* and neglecting higher order terms, then

$$T^{*4} \cong 4T_\infty{}^{*3}T^* - 3T_\infty{}^{*4} \quad (6)$$

By using equations (4) and (5), equation (2) reduces to

$$\rho C_p \frac{\partial T^*}{\partial t^*} = k\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{16\sigma^* T_\infty{}^{*3}}{3K_1{}^*}\frac{\partial^2 T^*}{\partial y^{*2}} \quad (7)$$

On introducing the following non-dimensional quantities

$$u = \frac{u^*}{u_0},\ y = \frac{y^* u_0}{\vartheta},\ t = \frac{t^* u_0{}^{*2}}{\vartheta},$$

$$\theta = \frac{(T^* - T_\infty{}^*)u_0 k}{q^*\vartheta},\ C = \frac{(C^* - C_\infty{}^*)Du_0}{\vartheta q_w{}^*},\ Gr = \frac{g\beta\vartheta^2 q^*}{k u_0{}^{*4}},$$

$$Gm = \frac{g\beta^*\vartheta^2 q_w{}^*}{D u_0{}^{*4}},\ Pr = \frac{\mu C_p}{k} = \frac{\vartheta\rho C_p}{k},\ \ \text{Sc} = \frac{\vartheta}{D},$$

$$\text{N} = \frac{K_1{}^* K}{4\sigma^* T_\infty{}^{*3}} \quad (8)$$

In view of equations (5) - (8), equations (1) – (3) reduce to the following dimensional form

$$\frac{\partial u}{\partial t} = Gr\ \theta + Gm\ C + \frac{\partial^2 u}{\partial y^2} \quad (9)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{a}\frac{\partial^2 \theta}{\partial y^2} \quad (10)$$

(10)

$$\frac{\partial c}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \quad (11)$$

The boundary conditions to the problem in the dimensionless form are

$$u = 0,\ \theta = 0,\ C = 0\ \ for\ all\ \ y \ge 0, \text{t} \le 0$$

$$\text{u} = \text{f(t)},\ \frac{\partial \theta}{\partial y} = -1,\ \frac{\partial c}{\partial y} = -1 \quad at\ y = 0, \text{t} > 0$$

$$u \to 0, \theta \to 0, C \to 0\ \ as\ \ y \to \infty, \text{t} > 0 \quad (12)$$

III. SOLUTION OF THE PROBLEM

Coupled linear partial differential equations (9) to (11) are solved subject to the initial and boundary conditions (12) by the usual Laplace transform method and the solutions are given as follows.

$$\theta = \frac{2\sqrt{t}}{\sqrt{a}}\left[\frac{\exp(-\eta^2 a)}{\sqrt{\pi}} - \eta\sqrt{a}\ \text{erfc}(\eta\sqrt{a})\right] \quad (13)$$

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$$c = \frac{2\sqrt{t}}{\sqrt{Sc}}\left[\frac{\exp(-\eta^2 Sc)}{\sqrt{\pi}} - \eta\sqrt{Sc}\ \mathrm{erfc}(\eta\sqrt{Sc})\right] \tag{14}$$

$$\begin{aligned} u = {} & erfc(\eta) - \frac{Gr}{3\sqrt{a}\,(1-a)}\, t^{\frac{3}{2}}\left[\frac{4}{\sqrt{\pi}}(1+\eta^2)\exp(-\eta^2) - \eta(6+4\eta^2)erfc(\eta)\right] \\ & + \frac{Gr}{3\sqrt{a}\,(1-a)}\, t^{\frac{3}{2}}\left[\frac{4}{\sqrt{\pi}}(1 + a\eta^2)\exp(-a\eta^2) - \eta\sqrt{a}(6+4a\eta^2)erfc(\eta\sqrt{a})\right] \\ & - \frac{Gc}{3\sqrt{Sc}\,(1-Sc)}\, t^{\frac{3}{2}}\left[\frac{4}{\sqrt{\pi}}(1 + \eta^2)\exp(-\eta^2) - \eta(6+4\eta^2)erfc(\eta)\right] \\ & + \frac{Gc}{3\sqrt{Sc}\,(1-Sc)}\, t^{\frac{3}{2}}\left[\frac{4}{\sqrt{\pi}}(1 + \eta^2 Sc)\exp(-\eta^2 Sc) - \eta(6+4\eta^2)erfc(\eta\sqrt{Sc})\right] \end{aligned} \tag{15}$$

Where $a = \frac{3NPr}{3N+4Pr}$ $and\ \eta = \frac{y}{2\sqrt{t}}$

Skin friction

Knowing the velocity field, the skin-friction at the plate can be obtained, which is non-dimensional form is given by

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = -\frac{1}{2\sqrt{t}}\left(\frac{\partial u}{\partial \eta}\right)_{\eta=0}$$

$$\tau = -\frac{1}{2\sqrt{t}}\left(-\frac{2}{\sqrt{\pi}} + \frac{2Gr\, t^{\frac{3}{2}}}{\sqrt{a}\,(1+\sqrt{a})} + \frac{2Gc\, t^{\frac{3}{2}}}{\sqrt{Sc}\,(1+\sqrt{Sc})}\right) \tag{16}$$

Nusselt number

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which is non-dimensional form is given, in terms of the Nusselt number, is given by

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = 1$$

Sherwood number:

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which is non-dimensional form is given, in terms of the Sherwood number, is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = 1$$

IV. RESULTS AND DISCUSSION

As a result of the numerical calculations, the dimensionless velocity, temperature and concentration distributions for the flow under consideration are obtained and their behavior have been discussed for variations in the governing parameters like Grashof number Gr, modified Grashof number Gm, Radiation parameter N, Prandtl number Pr and Schmidt number Sc.

The concentration profiles for different values of Schmidt number Sc are shown in figure 1. It is observed that concentration decreases as Schmidt number Sc increases. Figure 2 depicts the influence of the Radiation parameter N on the temperature field. It is seen that the temperature decreases as Radiation parameter N increases. The effect of Prandtl number Pr on the temperature profiles is illustrated in figure 3. It is seen that as the Prandtl number Pr increases, the temperature decreases.

Figures 4 and 5 show the effect of Grashof number Gr on the velocity field. It is noticed that the velocity increases with increasing Grashof number Gr for cooling of the plate, in case of heating of the plate the velocity increases as Grashof number Gr increases. Figures 6 and 7 show the effect of modified Grashof number Gm on the velocity field. It is noticed that the velocity increases with increasing modified Grashof number Gm for cooling of the plate, in case of heating of the plate the velocity increases as modified Grashof number Gm increases.

Figure 8 shows the effect of Radiation parameter N on the velocity field. It is found that the velocity decreases as Radiation parameter N increases. Figure 9 illustrates the effect of Schmidt number Sc on velocity profiles. It is seen that as Schmidt number Sc increases, the velocity decreases.

Table.1 shows the effects of different parameters on Skinfriction. It is noticed that Skinfriction increases with increasing Grashoff number (Gr), modified Grashof number (Gm) and decreases with increasing Schmidt number Sc, Radiation parameter N and Prandtl number Pr.

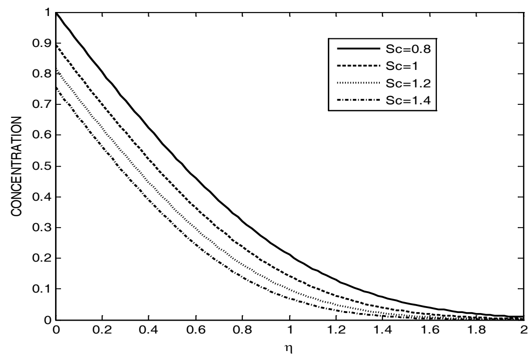

Fig.1. Effect of Schmidt number Sc on concentration profiles with N=2, t=0.2

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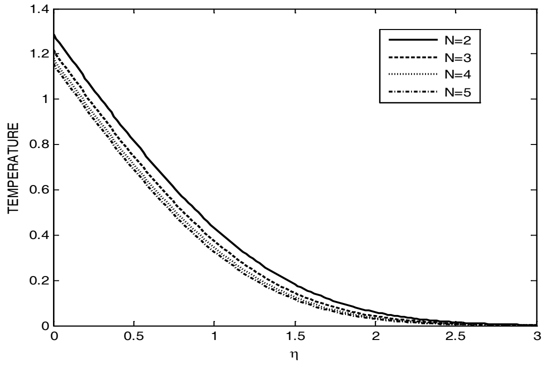

Fig.2. Effect of Radiation parameter N on temperature profiles with Pr=0.71, t=0.2

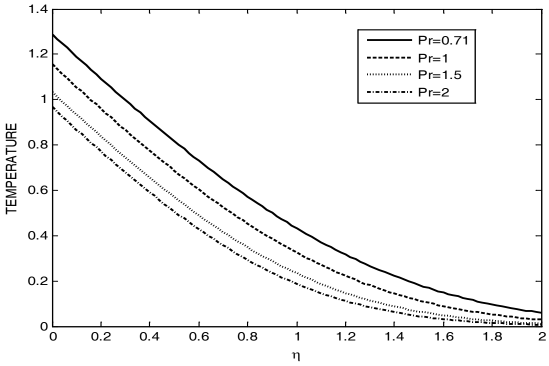

Fig.3. Effect of Prandtl number Pr on temperature profiles with N=2, t=0.2

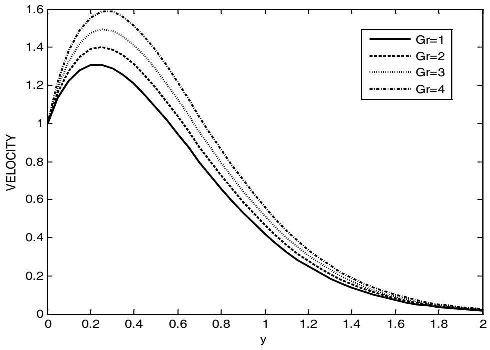

Fig.4. Effect of Grashof number Gr on velocity profiles with Gm=2, N=2, Sc=0.5, Pr=0.71, t=0.2

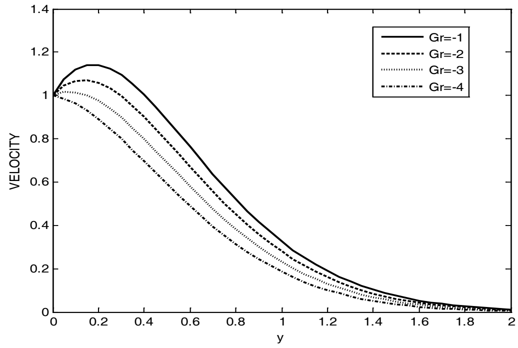

Fig.5 Effect of Grashof number Gr on velocity profiles with Gm=2, N=2, Sc=0.5, Pr=0.71, t=0.2

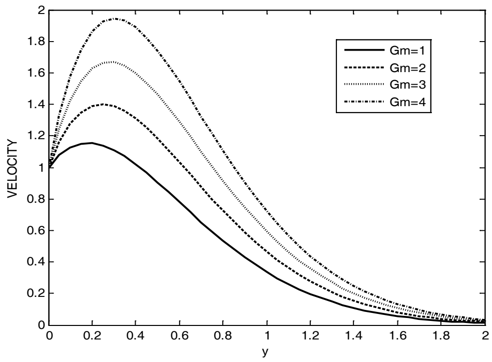

Fig.6. Effect of modified Grashof number Gm on velocity profiles with Gr=2, N=2, Sc=0.5, Pr=0.71, t=0.2

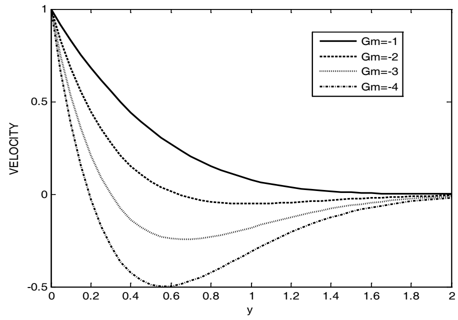

Fig.7. Effect of modified Grashof number Gm on velocity profiles with Gr=2, N=2, Sc=0.5, Pr=0.71, t=0.2

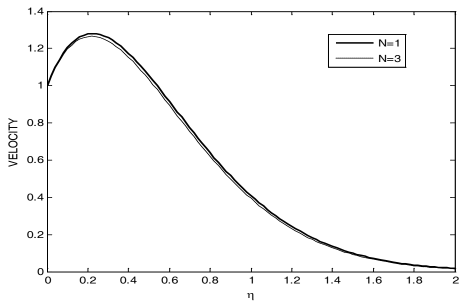

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Fig.8.Effect of thermal Radiation parameter N on velocity profiles with Gr=2, Gm=2, Sc=0.5, Pr=0.71, t=0.2

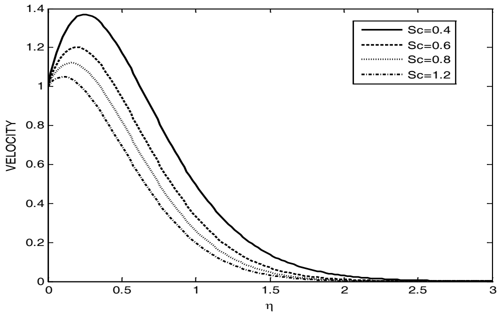

Fig.9. Effect of Schmidt number Sc on velocity profiles with Gr=2, Gc=2, N=2, Pr=0.71, t=0.2

Table.1.

Variation of numerical values of skin friction (τ) for different values of

Grashof number Gr, modified Grashof number Gm, Schmidt number Sc, Radiation parameter N, Prandtl number Pr

Gr	Gm	Sc	N	Pr	τ
1	2	0.5	2	0.71	1.7514
2	2	0.5	2	0.71	1.9215
3	2	0.5	2	0.71	2.0915
2	1	0.5	2	0.71	1.7558
2	2	0.5	2	0.71	1.9215
2	3	0.5	2	0.71	2.0872
2	2	0.2	2	0.71	2.2081
2	2	0.4	2	0.71	1.9775
2	2	0.6	2	0.71	1.8811
2	2	0.5	1	0.71	1.9943
2	2	0.5	2	0.71	1.9215
2	2	0.5	3	0.71	1.8953
2	2	0.5	2	0.71	1.9215
2	2	0.5	2	1	1.8724
2	2	0.5	2	1.5	1.8284

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