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Effect of Thermal Radiation on a Linearly Accelerated Vertical Plate with Variable Mass Diffusion and Uniform Temperature Distribution in a Rotating Medium

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Abstract— A theoretical study has been done on the effect of radiative heat transfer on a linearly accelerated vertical plate with variable mass diffusion and uniform temperature distribution where the plate is placed in a rotating medium. A grey fluid is considered here, which has the tendency to absorb and emit radiation without any scattering. The dimension parameters of various quantities such as temperature, concentration, etc., are converted into dimensionless quantities. The converted dimensionless quantities are introduced and substituted in the governing equations with appropriate boundary conditions and an exact solution is obtained using the Laplace Transform technique for the complex velocity. In this paper, the effects of primary velocity and secondary velocity were scrutinized by varying various parameters such as radiation, thermal Grashof's number, mass Grashof's number, and rotational parameter. The temperature and concentration profiles of the plate were also studied in this paper by varying Prandtl number and Schmidt's number respectively.

Keywords— Accelerated Vertical plate, mass diffusion, radiative heat transfer, uniform temperature, rotation, and concentration.

I. INTRODUCTION

Nowadays, cooling is one of the most important processes in each and every industry you come across. Cooling Systems today collectively account for 17% of electricity worldwide. By 2050, we will use 6 times more energy for cooling and we need 10 trillion kilowatt hours of electricity every year just for cooling by the year 2100. So it is necessary to improve the efficiency of the cooling process.
In cooling, radiative heat transfer and convection plays a very important role. Natural Convection which basically occurs due to the density difference has many applications like heat exchanger devices, cooling of molten's metal, desert coolers, petroleum reservoirs, frost formation, fiber and granular insulation, geothermal systems, geothermal energy recovery, flow through filtering devices and thermal energy storage.

Every object in the world emits some thermal radiation unless and until, the system reaches 0 K. When the system is subjected to very high temperatures and when there is a high-temperature difference between the systems, the effect of radiative heat transfer is quite significant. Radiative heat flows are encountered in many environmental and industrial processes such as heating and cooling chambers, fossil fuel combustion, energy processes, evaporation from large open water reservoirs, space vehicle re-entry, astrophysical flows, solar power technology etc.,
In nature, most of the processes are unsteady and both heat and mass transfer are observed simultaneously. Coupled heat and mass transfer have a wide variety of applications such as filtration, chemical catalytic reactors, and processes, spreading of chemical pollutants in plants and diffusion of medicine in blood veins.

In this paper, section I discusses the theoretical applications and the need for this concept. Section II describes the literature review of the papers similar to the above topic. In section III, basic formulation and mathematical analysis have been done whereas in section IV its results have been examined. The results are grouped and the conclusion is given in section V. In addition to that, the future scope of the paper has also been discussed in the same section. Section VI and Section VII deals with the nomenclature and the subscripts used in this paper.

II. RELATED WORK

E. Hemalatha et al. [1] had analyzed the effects of chemical reactions and the effect of heat and mass transfer on an MHD steady state 2-D flow of viscous incompressible fluid with convective surface boundary conditions in the presence of heat source/generation and the governing equations are solved using Runge-Kutta fourth order method with a shooting technique. VM Soundalgekar [2] examined the mass transfer effects of a vertical plate which is accelerated uniformly in the vertical direction with the presence of foreign mass. A.J.Chamka et al. [3] had perused the effects of mass transfer, chemical reaction and thermal radiation on a vertical plate which is accelerated exponentially and subjected to unsteady MHD with natural convection and the governing equations were solved using Laplace Transform method. A. G. V. Kumar et al. [4] had studied the effects of thermal diffusion and radiation on a vertical plate which is started impulsively and accelerated exponentially where the plate was subjected to an unsteady MHD flow with variable temperature and mass diffusion. M. C. Raju et al. [5] had researched the effects of radiation and mass transfer on a porous medium bounded by a porous surface which is subjected to a steady viscous fluid and suction was carried out at a constant viscosity in the presence of thermal radiation. Hossain MA et al. [6] had analyzed the radiation effects of a heated vertical flat plate subjected to natural and forced convection of an optically dense viscous incompressible fluid where the surface and free stream were maintained uniformly. R. C. Chaudhary et al. [7] inspected the effects of mass and heat transfer of a plate which is made to oscillate in a porous medium at a particular velocity and it is subjected to MHD free convection and the governing equations were solved using Laplace transform technique. K.Anwar [8] interpreted the effects of MHD on a vertical plate which is bounded by an infinite vertical plane surface experiencing unsteady 2-D laminar free convection flow of an incompressible, electrically conducting, viscous fluid, where the surface of the plate was maintained at a constant temperature. Agrawal A K et al. [9] had studied the heat and mass transfer effects of an infinite vertical plate which was initiated parabolically. A.R. Vijayalakshmi et al. [10] had scrutinized the combined effects of MHD and thermal radiation on an accelerated vertical plate which was placed in a rotating medium with variable temperatures and the governing equations were solved using Laplace Transform method. Jyotsna Rani Pattnaik et al. [11] had investigated mass transfer and radiation effects on MHD flow over an inclined vertical plate which was accelerated exponentially with variable temperature. Tasawar Hayat et al. [12] had probed the radiation effects of Jeffrey liquid over an inclined stretched cylinder which induced the mixed convection flow. The inclined stretched cylinder was impermeable by nature and the solutions were obtained using homotopy analysis approach.

Therefore, the present research is focused on scrutinizing the effect of radiative heat transfer on a linearly accelerated vertical plate with variable mass diffusion and uniform temperature distribution where the plate is placed in a rotating medium. The governing equations were made dimensionless and an apt solution is obtained using the Laplace transform technique in the form of exponential and complementary error functions.

III. BASIC EQUATION AND MATHEMATICAL ANALYSIS

Consider an infinite vertical plate occupying x'y' plane and normal to z' axis is placed in a viscous incompressible fluid. Both the fluid and the plate are at rest and have the same temperature and concentration. Here x' axis is assumed to be in a vertically upward direction and y' axis is normal to x' axis in the plane of the plate. The plate starts to move upwards with a velocity dt' at time t' > 0, along x' axis against the gravitational field, in the presence of thermal radiation. The plate and the fluid are subjected to a rigid rotation with a uniform angular velocity Ω' about the z' axis. Due to this motion, a 3-D flow of fluid is observed. The plate is also subjected to the variable mass diffusion. A grey fluid is considered here, which has the tendency to absorb and emit radiation without any scattering. Meanwhile, the temperature and concentration of the plate are lowered or raised to T_w' and C_w', respectively which is maintained constant afterward. The physical quantities depend only on z' and t' since the plate occupies the plane at z' = 0, which is of infinite extent. By Boussinesq's approximation, the unsteady flow is governed by the following equations:

$$\frac{\partial u'}{\partial t'} - 2\Omega' v' = g\beta(T' - T'_\infty) + \nu \frac{\partial^2 u'}{\partial z'^2} \quad (1)$$

$$\frac{\partial v'}{\partial t'} + 2\Omega' u' = \nu \frac{\partial^2 v'}{\partial z'^2} \quad (2)$$

$$\rho C_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial z'^2} - \frac{\partial q_r}{\partial z'} \quad (3)$$

$$\frac{\partial C'}{\partial t} = D \frac{\partial^2 C'}{\partial z'^2} \quad (4)$$

The initial and boundary conditions of the above equations are given below:

$$t' \le 0 : u' = 0,\ v' = 0,\ T' = T'_\infty,\ C' = C'_\infty \quad \text{for all } z'$$

$$t' > 0 : u' = dt',\ v' = 0,\ T' = T'_w,\ C' = C'_w + \left(C'_w - C'_\infty\right) \quad \text{at } z' = 0$$

$$u' \to 0,\ v' \to 0,\ T' \to T_\infty,\ C' \to C'_\infty \quad \text{as } z' \to \infty$$

With the help of Roseland's approximation and Taylor's series, the radiating heat flux term is modified and hence (3) becomes

$$\rho C_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial z'^2} + 16a^* \sigma T'^3_\infty (T'_\infty - T') \quad (5)$$

On introducing and substituting the following dimensionless quantities, initial and boundary conditions,

$$q = 0,\ \ \theta = 0,\ \ C = 0, \quad \text{for all } z \le 0 \ \&\ t \le 0$$

$$t > 0: \quad q = t,\ \ \theta = 1,\ \ C = t, \quad \text{at } z = 0$$

$$q = 0,\ \ \theta \to 0,\ \ C \to 0, \quad \text{as } z \to \infty$$

$$(u,v) = \frac{(u',v')}{(vd)^{\frac{1}{3}}},\ \ t = t'\left(\frac{d^2}{v}\right)^{\frac{1}{3}},\ \ z = z'\left(\frac{d}{v^2}\right)^{\frac{1}{3}},\ \ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},$$

$$Gr = \frac{g\beta(T'_w - T'_\infty)}{d},\ \ C = \frac{C' - C'_\infty}{C'_w - C'_\infty},\ \ Gc = \frac{g\beta^*(T'_w - T'_\infty)}{d},$$

$$\Pr = \frac{\mu C_p}{k},\ \ \Omega = \Omega'\left(\frac{v}{d^2}\right)^{\frac{1}{3}},\ \ R = \frac{16a^* v\sigma T'^3_\infty}{k}\left(\frac{v}{d^2}\right)^{\frac{1}{3}}$$

and the complex velocity q = u + iv where i = $\sqrt{-1}$, in (1) to (4), the governing equations become

$$\frac{\partial q}{\partial t} + 2\Omega i q = Gr\theta + GcC + \frac{\partial^2 q}{\partial z^2} \qquad (6)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial z^2} - \frac{R}{\Pr}\theta \qquad (7)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} \qquad (8)$$

In the nomenclature, all the physical variables are defined. The solutions are obtained for (6) to (8), where the boundary conditions are substituted and an apt solution is derived by Laplace-transform technique as follows:

$$C = t(1 + 2\eta^2 Sc)\cdot erfc(f11) - \frac{2\eta\sqrt{Sc}}{\sqrt{\pi}}(e^{-\eta^2 Sc}) \qquad (9)$$

$$\theta = \frac{1}{2}\left[e^{-2\eta\sqrt{\Pr}\sqrt{at}}\cdot erfc(f5) + \left[e^{2\eta\sqrt{\Pr}\sqrt{at}}\cdot erfc(f6)\right]\right]$$

(10)

$$\begin{aligned}
q = {} & \frac{t}{2}\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) + e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& - \frac{\eta\sqrt{t}}{2\sqrt{m}}\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) - e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& + X\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) + e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& - Xe^{bt}\left[e^{-2\eta\sqrt{(b+m)t}}\cdot erfc(f3) + e^{2\eta\sqrt{(b+m)t}}\cdot erfc(f4)\right] \\
& + X\left[e^{-2\eta\sqrt{\Pr}\sqrt{at}}\cdot erfc(f5) + e^{2\eta\sqrt{\Pr}\sqrt{at}}\cdot erfc(f6)\right] \\
& - Xe^{bt}\left[e^{-2\eta\sqrt{\Pr}\sqrt{(a+b)t}}\cdot erfc(f7) + e^{2\eta\sqrt{\Pr}\sqrt{(a+b)t}}\cdot erfc(f8)\right] \\
& + \frac{Y}{2}\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) + e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& + \frac{Yct}{2}\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) + e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& - \frac{Yc\eta\sqrt{t}}{2\sqrt{m}}\left[e^{-2\eta\sqrt{mt}}\cdot erfc(f1) - e^{2\eta\sqrt{mt}}\cdot erfc(f2)\right] \\
& - \frac{Ye^{ct}}{2}\left[e^{-2\eta\sqrt{(c+m)t}}\cdot erfc(f9) + e^{2\eta\sqrt{(c+m)t}}\cdot erfc(f10)\right] \\
& - Yc\left[t(1 + 2\eta^2 Sc)\cdot erfc(f11) - \frac{2\eta\sqrt{Sc}}{\sqrt{\pi}}(e^{-\eta^2 Sc})\right] \\
& + \frac{Ye^{ct}}{2}\left[e^{-2\eta\sqrt{Sc}\sqrt{ct}}\cdot erfc(f12) + e^{2\eta\sqrt{Sc}\sqrt{ct}}\cdot erfc(f13)\right] \\
& - Y\cdot erfc(f11)
\end{aligned}$$

(11)

where

$$a = \frac{R}{\Pr},\ \ b = \frac{R - m}{1 - \Pr},\ \ m = 2\Omega i,\ \ c = \frac{m}{Sc - 1},$$

$$\eta = \frac{z}{2\sqrt{t}},\ X = \frac{Gr}{2b(1 - \Pr)},\ \ Y = \frac{Gc}{c^2(1 - Sc)},$$

$$f1 = \eta - \sqrt{mt},\ f2 = \eta + \sqrt{mt},\ f3 = \eta - \sqrt{(b+m)t},$$

$$f4 = \eta + \sqrt{(b+m)t},\ f5 = \eta\sqrt{\Pr} - \sqrt{at},$$

$$f6 = \eta\sqrt{\Pr} + \sqrt{at},\ f7 = \eta\sqrt{\Pr} - \sqrt{(a+b)t},$$

$$f8 = \eta\sqrt{\Pr} + \sqrt{(a+b)t},\ f9 = \eta - \sqrt{(c+m)t},$$

$$f10 = \eta + \sqrt{(c+m)t},\ f11 = \eta\sqrt{Sc},\ f12 = \eta\sqrt{Sc} - \sqrt{ct},$$

$$f13 = \eta\sqrt{Sc} + \sqrt{ct}$$

In the equation, the error function and the argument of the complementary error function are complex. So we use the formula given by Abramowitz and Stegun [13] to calculate the velocity.

$$erf(a + ib) = erf(a) + \frac{e^{-a^2}}{2a\pi}\left[1 - \cos(2ab) + i\sin(2ab)\right]$$

$$+ \frac{e^{-a^2}}{2a\pi}\sum_{n=1}^{\infty}\frac{e^{-(n^2/4)}}{n^2 + 4a^2}\left[f_n(a,b) + ig_n(a,b)\right] + \varepsilon(a,b)$$

where,

$$f_n = 2a - 2a \cosh(nb) \cos(2ab) + n \sinh(nb) \sin(2ab)$$

$$g_n = 2a \cosh(nb) \sin(2ab) + n \sinh(nb) \cos(2ab)$$

$$|\varepsilon(a,b)| \approx 10^{-16} |erf(a+ib)|$$

IV. Results and Discussion

The expressions for u and v are obtained using the above formula and the following graphs are drawn using the solutions of q, θ, C and the characteristics of the different parameters are scrutinized. The primary velocity and secondary velocity profiles are drawn for the air system.

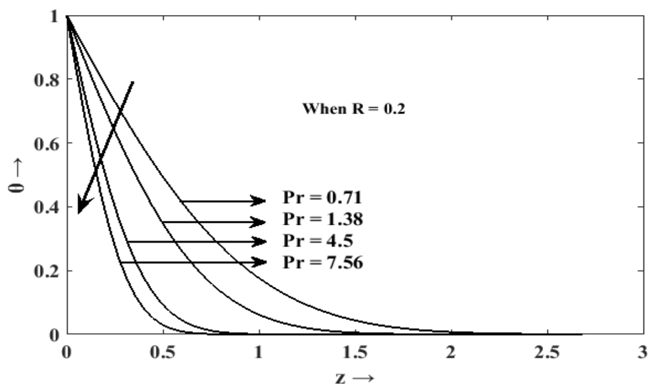

Figure 1. Temperature Profile for varying Pr

Figure 1 shows the temperature profile for different fluids having different Pr. From the graph, a reduction in temperature is observed when there is an increase in Pr and for high values of Pr, the thermal boundary layer thickness is less. Higher the Prandtl number, faster is the achievement of the steady-state and lesser is the thermal boundary layer thickness.

Figure 2 shows the concentration profile for different Sc. It is evident from the graph that the increase in the Schmidt Number decreases the concentration. Higher the Schmidt number, faster is the achievement of the steady-state and lesser is the concentration boundary layer thickness.

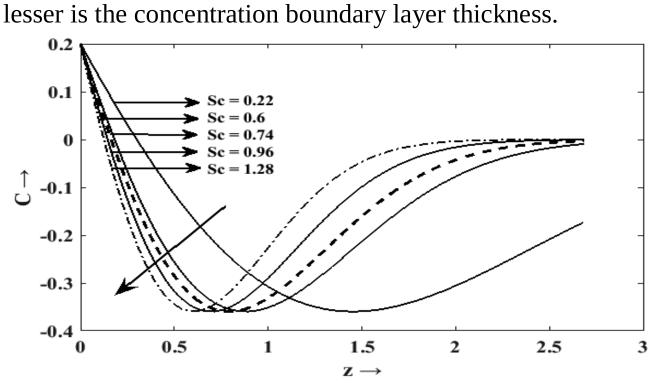

Figure 2. Concentration Profile for varying Sc

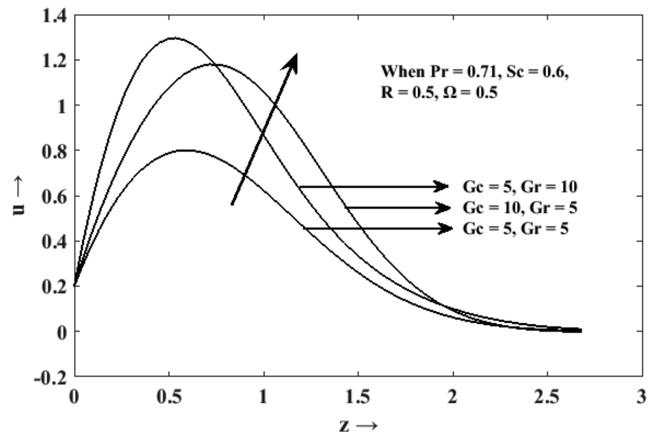

Figure 3. Primary Velocity profiles for different Gr and Gc when R = Ω

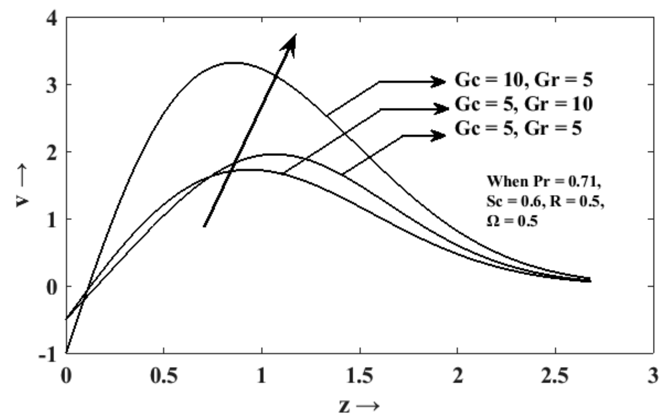

Figure 4. Secondary Velocity profiles for different Gr and Gc when R = Ω

Figure 3 and Figure 4 shows primary and secondary velocity profiles for different Gr and Gc when R = Ω respectively. It is clear that the effect of Gr is more in increasing the primary velocity and the effect of Gc is more in increasing the secondary velocity of the plate. The same trend is observed in figure 5 and 6 where the profile is discussed for the condition when R< Ω.

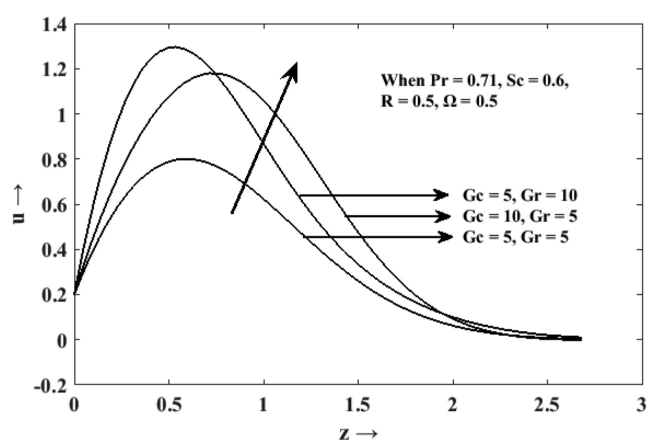

Figure 5. Primary Velocity profiles for different Gr and Gc when R < Ω

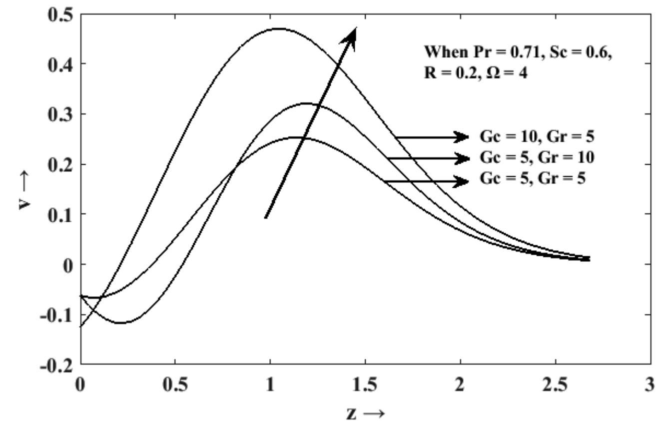

Figure 6. Secondary Velocity profiles for different Gr and Gc when R < Ω

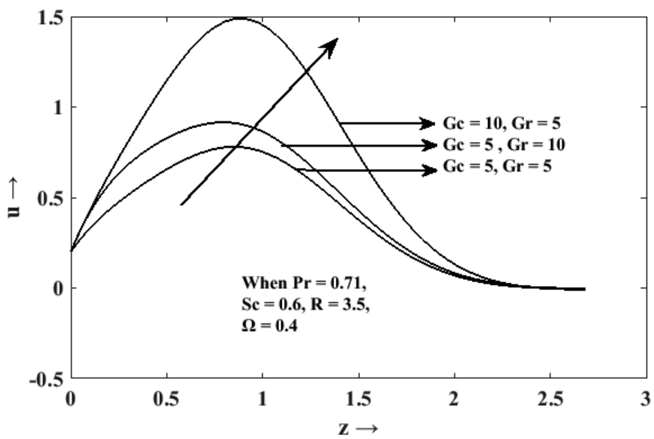

Figure 7. Primary Velocity profiles for different Gr and Gc when R > Ω

Figure 7 and Figure 8 shows primary and secondary velocity profiles for different Gr and Gc when R > Ω respectively. It is evident that the effect of Gc is more in increasing both primary velocity and secondary velocity when compared to the effect of Gr in increasing the primary and secondary velocities of the plate.

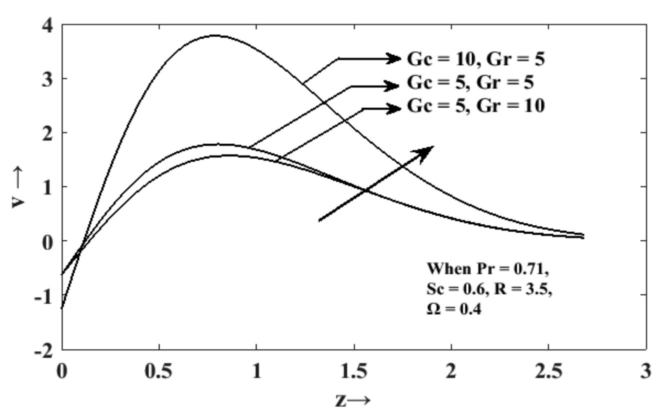

Figure 8. Secondary Velocity profiles for different Gr and Gc when R > Ω

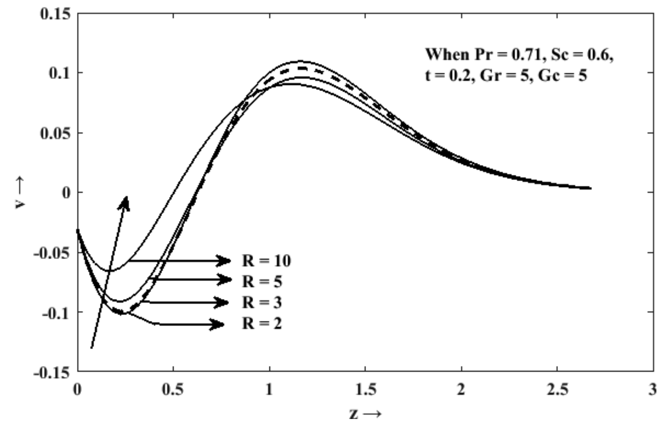

Figure 9. Primary Velocity profiles for different R when Ω = 8

Figure 9 shows the primary velocity profile for different R when Ω = 8. It says that the primary velocity decreases with the increase in the radiation parameter. Higher the value of R, lesser is the velocity boundary layer thickness.

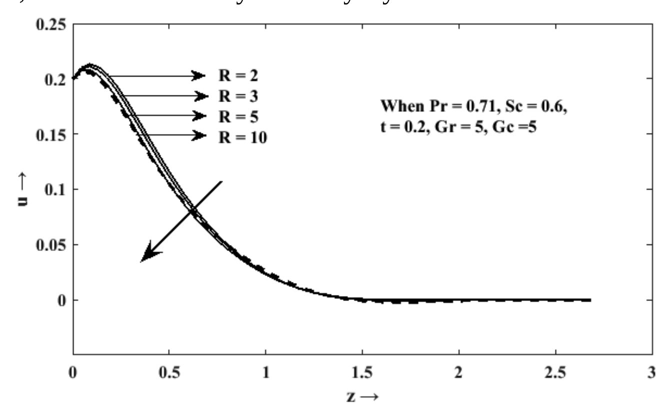

Figure 10. Secondary Velocity profiles for different R when Ω = 8

Figure 10 shows the secondary velocity profile for different R when Ω = 8. It says that the secondary velocity increases with the increase in the radiation parameter.

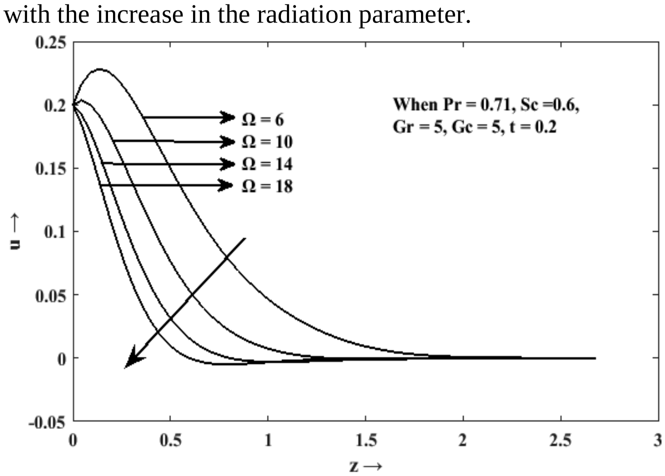

Figure 11. Primary Velocity profiles for different Ω when R = 2

Figure 11 shows the primary velocity profile for different Ω when R = 2. It is observed that as the dimensionless rotational parameter "Ω" increases, the primary velocity u decreases. Higher the rotational parameter, lesser is the velocity boundary layer thickness.

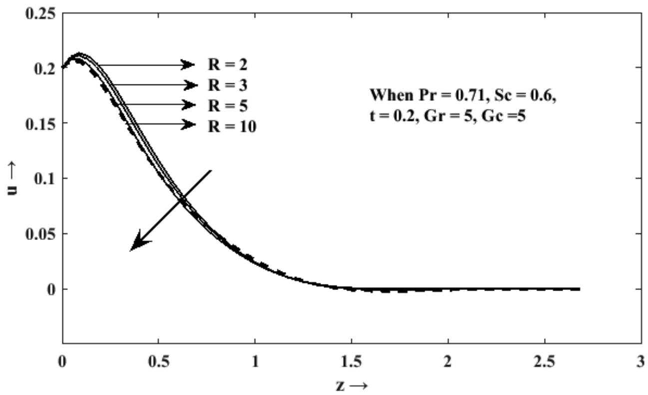

Figure 12. Secondary Velocity profiles for different Ω when R = 2

Figure 12 shows secondary velocity profiles for different Ω when R = 2. It is observed that as the dimensionless rotational parameter "Ω" increases, the secondary velocity v increases.

V. CONCLUSION AND FUTURE SCOPE

Therefore, a theoretical study has been done on the effect of radiative heat transfer on a linearly accelerated vertical plate with variable mass diffusion and uniform temperature distribution where the plate is placed in a rotating medium. The governing equations are simplified using dimensionless parameters and the solution is obtained through the method of Laplace Transform. The inference of the above paper can be summarized as follows:

(i) Primary velocity decreases with increase in the dimensionless rotational parameter Ω and radiation parameter R.
(ii) Secondary velocity increases with increase in the dimensionless rotational parameter Ω and radiation parameter R.
(iii) A decrease in the concentration is observed when there is an increase in Schmidt number.
(iv) A reduction in the temperature and thermal boundary layer thickness is observed when there is an increase in Prandtl number.
(v) When R = Ω and R < Ω, the effect of Gr is more in increasing the primary velocity of the plate and the effect of Gc is more in increasing the secondary velocity of the plate.
(vi) When R > Ω, the effect of Gc is more in increasing both primary velocity and secondary velocity when compared to the effect of Gr in primary and secondary velocities of the plate.

The above work can be extended by replacing the grey fluid with nanofluids.

VI. NOMENCLATURE

a^* – Absorption coefficient
C – Dimensionless concentration
C' – Concentration
C_p – Specific heat at constant pressure
D – Mass diffusion coefficient
Gc – Mass Grashof number
Gr – Thermal Grashof number
g – Acceleration due to gravity
k – Thermal conductivity of the fluid
Pr – Prandtl number
q_r – Radiative heat flux
R – Radiation parameter
Sc – Schmidt number
T' – Temperature of the fluid near the plate
T_w' – Temperature of the plate
T_∞' – Temperature of the fluid far away from the plate
t – Dimensionless time
t' – Time
u – Dimensionless velocity of the fluid in x' direction
u' – Velocity of the fluid in x' direction
v – Dimensionless velocity of the fluid in y' direction
v' – Velocity of the fluid in y' direction
y' – Coordinate axis normal to the x' axis
z – Dimensionless coordinate axis normal to the plate
z' – Coordinate axis normal to the plate
β – Volumetric coefficient of thermal expansion
β' – Volumetric coefficient of thermal expansion with concentration
μ – Coefficient of viscosity
ν – Kinematic viscosity
Ω – Dimensionless rotation parameter
Ω' – Rotation Parameter
ρ – Density
σ – Stefan – Boltzmann Constant
θ – Dimensionless temperature
erf – Error function
erfc – Complementary error function

VII. SUBSCRIPTS

w – conditions on the wall
∞ – free stream conditions

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