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SORET-DUFOUR, RADIATION AND HALL EFFECTS ON UNSTEADY MHD FLOW OF A VISCOUS INCOMPRESSIBLE FLUID PAST AN INCLINED PLATE EMBEDDED IN POROUS MEDIUM

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Abstract. A Study is presented with Soret-Dufour, Hall and radiation effects on unsteady MHD flow of a viscous incompressible fluid past an inclined porous plate immersed in porous medium. The governing equations of non-dimensional forms of flow field were solved numerically using Crank-Nicolson implicit finite difference method. The results are obtained for velocity, temperature and concentration. The effects of various parameters are discussed on flow variables and are presented through graphs and tables.

Keywords: MHD, Soret effect, Dufour effect, Hall effect, Thermal radiation, porous medium, heat and mass transfer, Crank-Nicolson method

AMS Subject Classification: 76W05; 76R50; 78A40 and 76M20 (2010 MSC)

1. Introduction

In engineering and applied physics, Soret-Dufour, Hall and radiation effects play important role. The analysis of such flow has been applied in MHD generators, chemical engineering, geothermal energy and astrophysical study. The existence of pure fluid in nature is rather impossible. Molecules are transported in multi component mixture driven by temperature gradient, is known as Soret effect and inverse phenomena is Dufour effect. Hall effect arises in plasma when electrons are able to drift with magnetic field but ions cannot.

Sparrow and cess [1] investigated the effect of magnetic field on free convection heat transfer. Jana and kanch [2] have analyzed hall effect on unsteady couettee flow under boundary layer approximation. Rao et al. [3] studied chemical reaction effects on an unsteady MHD free convective flow past an infinite vertical porous plate with constant suction and heat source. Ghosh [4] has investigated the effects of hall current on MHD couettee flow in a rotating system with arbitrary magnetic field. Nadeem et al. [5] studied the effects of Hall current on unsteady flow of a Non-Newtonian fluid in a rotating system.

Pandya and Shukla [6] investigated Soret Dufour and radiation effects on unsteady MHD flow past an impulsively started inclined porous plate with variable temperature and mass diffusion. Laxmi et al. [7] analyzed numerically the effects of Dufour and Soret on an unsteady MHD flow past an infinite vertical porous plate with thermal radiation. Ram

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Reddy [8] studied effects of Soret and Dufour on mixed convection heat and mass transfer4 in a micro polar fluid with heat and mass flows.
The objective of this paper is to analyze the effects of Soret-Dufour, Hall and radiation on inclined porous plate in presence of variable temperature and concentration. The governing equation of non-dimensional form of flow fields are solved numerically using Crank-Nicolson implicit finite difference method. The effect of difference physical parameters on velocity, temperature and concentration are discussed through graphically.

2. Mathematical Analysis

Consider an unsteady MHD flow of a viscous incompressible electrically conducting fluid past an infinite inclined porous plate with variable temperature and concentration with Soret-Dufour, radiation and Hall effects has been studied. The plate is embedded in porous medium and inclined at angle λ to vertical. x'-axis is taken along the plate and y-axis is normal to it. A uniform magnetic field B_0 is taken in y-axis and plate is electrically non-conducting. Consider z-axis normal to xy plane. Let velocity $\overrightarrow{V'}$ and magnetic field $\overrightarrow{H'}$ be components (u', v', w') and (H'_x, H'_y, H'_z) respectively.
Equation of continuity:

$$\frac{\partial v'}{\partial y'} = 0 \Rightarrow v' = -v_0(constant) \tag{1}$$

from Maxwell's electromagnetic field equations

$$\frac{\partial H'_y}{\partial y'} = 0 \tag{2}$$

Here magnetic Reynolds number is very very small, so induced magnetic field is negligible in comparison to applied magnetic field, hence

$$H'_x = 0 = H'_z \, and \, H'_y = B_0 \tag{3}$$

Let (J'_x, J'_y, J'_z) be components of electric current density $\overrightarrow{J'}$, by conservation of electric charge $\nabla.\overrightarrow{J'} = 0$ implies

$$J'_y = constant \tag{4}$$

account of non conducting plate $J'_y = 0$. To neglect polarized effect, we have

$$\overrightarrow{E'} = 0 \tag{5}$$

hence

$$\overrightarrow{J'} = (J'_x, 0, J'_z), \quad \overrightarrow{H'} = (0, B_0, 0), \quad \overrightarrow{V'} = (u', v_0, w') \tag{6}$$

Taking Hall effect into account, the generalized Ohm's law

$$\overrightarrow{J'} + \frac{w_e\tau_e}{B_0}(\overrightarrow{J'} \times \overrightarrow{H'}) = \sigma\left(\overrightarrow{E'} + \overrightarrow{V'} \times \overrightarrow{H'} + \frac{1}{e\eta_e}\nabla p_e\right) \tag{7}$$

where $\overrightarrow{V'}, w_e, \tau_e, e, \eta_e, p_e, \sigma, \overrightarrow{E'}$ are velocity vector, electron frequency, electron collision time, electron charge, number of density of electron, electron pressure, electric conductivity, electric field respectively. It is considered that $w_e\tau_e \sim 0$. From equation 6 and 7, we have

$$\begin{aligned} J'_x &= \frac{\sigma B_0}{1+m^2}(mu' - w') \\ J'_z &= \frac{\sigma B_0}{1+m^2}(u' + mw') \end{aligned} \tag{8}$$

here u' along x'-axis and w' along z'-axis and $m = w_e \tau_e$ is Hall parameter.
Momentum equations:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} + g\gamma(T' - T'_\infty)\,cos(\lambda) + g\gamma^*(C' - C'_\infty)\,cos(\lambda) - \frac{\sigma B_0^2}{\rho(1+m^2)}(u' + mw') - \frac{\nu u'}{K'} \tag{9}$$

$$\frac{\partial w'}{\partial t'} + v'\frac{\partial w'}{\partial y'} = \nu\frac{\partial^2 w'}{\partial y'^2} + \frac{\sigma B_0^2}{\rho(1+m^2)}(mu' - w') - \frac{\nu w'}{K'} \tag{10}$$

Energy equation:

$$\rho C_p\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + \frac{\rho D_m K_T}{c_s}\frac{\partial^2 C'}{\partial y'^2} \tag{11}$$

continuity equation of mass transfer:

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T'}{\partial y'^2} \tag{12}$$

here molecular diffusivity is D_m, coefficient of volume expansion for mass transfer is γ^*, volumetric coefficient of thermal expansion is γ, magnetic induction is B_0, velocity component along x'-axis, y'-axis and z'-axis are u', v' and w' respectively, permeability of porous medium is K', electrical conductivity is σ, gravitational acceleration is g, fluid density is ρ, thermal conductivity of fluid is k, specific heat of constant pressure is c_p, thermal diffusion ratio is K_T, dimensional temperature is T', temperature of free stream is T'_∞ dimensional concentration is C', concentration of free stream is C'_∞, kinematic viscosity is ν , radiation of heat flux along y'-axis is q_r, mean fluid temperature is T_m.
Boundary and initial conditions are given as:

$$\begin{aligned} &t' \le 0 \quad u' = 0 \quad w' = 0 \quad T' = T'_\infty \quad C' = C'_\infty \quad \forall y' \\ &t' > 0 \quad u' = u_0 \quad v' = -v_0 \quad w' = 0 \quad T' = T' + (T'_w - T'_\infty)e^{At'}, \\ &C' = C' + (C'_w - C'_\infty)e^{At'} \quad at\, y' = 0 \\ &u' = 0 \quad w' = 0 \quad T' \to \infty \quad C' \to \infty \quad y' \to \infty \end{aligned} \tag{13}$$

where, $A = \frac{v_0^2}{\nu}$, tmeperature and concentration of plate are T'_w and C'_w respectively.
To use the Roseland approximation, radiative heat flux is given by

$$q_r = -\frac{4\sigma}{3k_m}\frac{\partial T'^4}{\partial y'} \tag{14}$$

here Stefan Boltzmann constant and absorption coefficient are σ and k_m respectively. In this case temperature difference are very very small within flow, such that T'^4 can be expressed linearly with temperature. It is realized by expanding in a Taylor series about T'_∞ and neglecting higher order terms, so

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \tag{15}$$

hence, by equation 14 and equation 15, equation 11 is reduced

$$\rho C_p\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma T'^3_\infty}{3k_m}\frac{\partial^2 T'}{\partial y'^2} + \frac{\rho D_m K_T}{c_s}\frac{\partial^2 C'}{\partial y'^2} \tag{16}$$

In order to yield non-dimensional partial differential equations, introducing following dimensional quantities:

$$u = \frac{u'}{u_0},\ t = \frac{t'v_0^2}{\nu},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ C = \frac{C' - C'_\infty}{C'_w - C'_\infty},\ Gm = \frac{\nu g\alpha^*(C'_w - C'_\infty)}{u_0 v_0^2},$$
$$Gr = \frac{\nu g\alpha(T'_w - T'_\infty)}{u_0 v_0^2},\ Du = \frac{D_m K_T(C'_w - C'_\infty)}{c_s c_p \nu(T'_w - T'_\infty)},\ Sr = \frac{D_m K_T(T'_w - T'_\infty)}{T_m \nu(C'_w - C'_\infty)}, \tag{17}$$
$$K = \frac{v_0^2 K'}{\nu^2,},\ Pr = \frac{\mu c_p}{k},\ M = \frac{\sigma B_0^2 \nu}{\rho v_0^2},\ R = \frac{4\sigma T_\infty'^3}{k_m k},\ Sc = \frac{\nu}{D_m},\ y = \frac{y' v_0}{\nu},\ w = \frac{w'}{u_0}$$

By virtue of equations 17, we yield dimensionless form of equations 9, 10, 12 and 16 respectively

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\, cos(\lambda) + Gm\, cos(\lambda) - \left(\frac{M}{1+m^2} + \frac{1}{K}\right) u - \left(\frac{mM}{1+m^2}\right) w \tag{18}$$

$$\frac{\partial w}{\partial t} - \frac{\partial w}{\partial y} = \frac{\partial^2 w}{\partial y^2} - \left(\frac{M}{1+m^2} + \frac{1}{K}\right) w + \left(\frac{mM}{1+m^2}\right) u \tag{19}$$

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{Pr}\left(1 + \frac{4R}{3}\right)\frac{\partial^2 \theta}{\partial y^2} + Du\frac{\partial^2 C}{\partial y^2} \tag{20}$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} + Sr\frac{\partial^2 \theta}{\partial y^2} \tag{21}$$

with following boundary and initial conditions in dimensionless form are:

$$\begin{gathered} t \le 0 \quad u = 0 \quad w = 0 \quad \theta = 0 \quad C = 0 \quad \forall y \\ t > 0 \quad u = 1 \quad w = 0 \quad \theta = e^t \quad C = e^t \quad at\ y = 0 \\ u = 0 \quad w = 0 \quad \theta \to 0 \quad C \to 0 \quad y \to \infty \end{gathered} \tag{22}$$

Now, it is useful to calculate physical quantities for primary interest, these are coefficient of skin-friction at the wall along x-axis τ_1, coefficient of skin-friction at the wall along z-axis τ_2, Nusselt number Nu and Sherwood number Sh. Dimensionless forms of these physical quantities are:

$$\begin{aligned} \tau_1 &= \left(\frac{\partial u}{\partial y}\right)_{y=0} \\ \tau_2 &= \left(\frac{\partial w}{\partial y}\right)_{y=0} \\ Nu &= -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} \\ Sh &= -\left(\frac{\partial C}{\partial y}\right)_{y=0} \end{aligned} \tag{23}$$

3. Method of Solutions

Equations 18 to 21 are non linear partial differential equations, are solved using initial boundary conditions 22 . Till now, exact solutions of these types of partial differential equations are not possible. Hence, it is solved by Crank-Nicolson implicit finite difference method for numerical solution. Equations 18, 19, 20 and 21 are as expressed

$$\begin{aligned} &\frac{u_{i,j+1}-u_{i,j}}{\Delta t} - \frac{u_{i+1,j}-u_{i,j}}{\Delta y} = \\ &\left(\frac{u_{i-1,j}-2u_{i,j}+u_{i+1,j}-2u_{i,j+1}+u_{i+1,j+1}+u_{i-1,j+1}}{2(\Delta y)^2}\right) \\ &+Gr\,cos(\lambda)\left(\frac{\theta_{i,j+1}-\theta_{i,j}}{2}\right)+Gm\,cos(\lambda)\left(\frac{Ci,j+1-Ci,j}{2}\right) \\ &-\left(\frac{M}{1+m^2}+\frac{1}{K}\right)\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right)-\left(\frac{mM}{1+m^2}\right)\left(\frac{w_{i,j+1}+w_{i,j}}{2}\right) \end{aligned} \tag{24}$$

$$\begin{aligned} &\frac{w_{i,j+1}-w_{i,j}}{\Delta t} - \frac{w_{i+1,j}-w_{i,j}}{\Delta y} = \\ &\left(\frac{w_{i-1,j}-2w_{i,j}+w_{i-1,j}-2w_{i,j+1}+w_{i+1,j+1}+w_{i-1,j+1}}{2(\Delta y)^2}\right) \\ &-\left(\frac{M}{1+m^2}+\frac{1}{K}\right)\left(\frac{uw_{i,j+1}+w_{i,j}}{2}\right)+\left(\frac{mM}{1+m^2}\right)\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right) \end{aligned} \tag{25}$$

$$\begin{aligned} &\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t} - \frac{\theta_{i+1,j}-\theta_{i,j}}{\Delta y} = \\ &\frac{1}{Pr}\left(1+\frac{4R}{3}\right)\left(\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i-1,j}-2\theta_{i,j+1}+\theta_{i+1,j+1}+\theta_{i-1,j+1}}{2(\Delta y)^2}\right) \\ &+Du\left(\frac{C_{i-1,j}-2u_{i,j}+C_{i-1,j}-2C_{i,j+1}+C_{i+1,j+1}+C_{i-1,j+1}}{2(\Delta y)^2}\right) \end{aligned} \tag{26}$$

$$\begin{aligned} &\frac{C_{i,j+1}-C_{i,j}}{\Delta t} - \frac{C_{i+1,j}-C_{i,j}}{\Delta y} = \\ &\frac{1}{Sc}\left(\frac{C_{i-1,j}-2u_{i,j}+C_{i-1,j}-2C_{i,j+1}+C_{i+1,j+1}+C_{i-1,j+1}}{2(\Delta y)^2}\right) \\ &+Sr\left(\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i-1,j}-2\theta_{i,j+1}+\theta_{i+1,j+1}+\theta_{i-1,j+1}}{2(\Delta y)^2}\right) \end{aligned} \tag{27}$$

Corresponding boundary and initial conditions are

$$\begin{aligned} &u_{i,0}=0 \quad w_{i,0}=0 \quad \theta_{i,0}=0 \quad C_{i,0}=0 \quad \forall\, i \\ &u_{0,j}=1 \quad w_{0,j}=0 \quad \theta_{0,j}=e^{j\Delta t} \quad C_{0,j}=e^{j\Delta t} \\ &u_{L,j}=0 \quad w_{L,J}=0 \quad \theta_{L,j}\to 0 \quad C_{L,j}\to 0 \end{aligned} \tag{28}$$

Here, index I pertains to y, j pertains to time t, $\Delta t = t_{j+1} - t_j$ and $\Delta y = y_{i+1} - y_i$. Knowing values of u, w, θ and C at t, we calculate these values for $t + \Delta t$ as follows, we calculate these values for we substitute $i = 1, 2, 3, \cdots L - 1$, where L corresponds to ∞. Now equations 24 to 27 given tridiagonal system of equations, is solved by Thomas algorithm as discussed in Carnahan et al. [9]. Then θ and C are known for all values of y at $t + \Delta t$. Replacing values of θ and C in equations 24, 25 and solved by same with initial and boundary conditions, we have solutions for u and w till desired time t. Crank-Nicolson implicit finite difference method is second order method $\left(o\left(\Delta t^2\right)\right)$ in time and has no limitation for space and time steps, that is, the method is unconditionally stable. Computation were executed for $\Delta y = 0.1$, $\Delta t = 0.001$ and repeated and till $y = 4$, procedure is repeated.

4. Result and Discussion

In order to see into physical problem, numerical results for dimensionless velocities u and w, temperature θ and concentration C are discussed with help of graphs by assigning numerical values of thermal Grashof number Gr, solute Grashof number Gm, Soret number Sr, Dufour number Du, Schmidt number Sc, Prandtl number Pr, radiation parameter R, Hall parameter m, magnetic parameter M, permeability of porous medium K and inclination angle λ.
On increasing Sr, it is clear in figures 1 and 2 that velocities u, w increase and concentration C increases. velocities u and w decrease in figure 3 and concentration C decreases in figure 4 as Sc increases. in figure 5, remarkable effect has been found that on increasing Pr velocity u first increases then decreases fast while velocity w increases. Temperature θ in figure 6 decreases when Pr increases. In figure 7, there exists also interesting result in concentration. It is seen that first concentration increases fast then decreases when Pr increases.
In figures 8 and 9 it is analyzed that temperature θ first decreases after increases and concentration C has surprised effect that sequentially increment, decrement and increment has been found in it as Dufour number Du increases. Velocities u and w increase in figure 10 and 11 when Gm and Gr increase respectively. It is analyzed in figure 12 that velocity u decreases while velocity w increases when M increases respectively. On the other hand, in figure 13 u and w both increase as hall parameter m increases.
It is found in figures 14, 15 and 16 that velocities u and w increase, temperature θ and concentration C decreases as radiation parameter R increases respectively. It is discussed in figures 17 and 19 that velocities u and w increase when permeability of porous medium K and time t increase respectively while in figure 18, velocities u and w both decrease as inclination angle λ increases. It is also seen in figures 20 and 21 that temperature θ and concentration C increase when time t increases.
Velocities u and w decrease in figure 18 as inclination angle λ increases. Table 1 depict that on increasing λ, Sc and M skin friction coefficient τ_1 along wall x-axis decreases while skin friction coefficient τ_2 along wall z-axis decreases as λ and Sc increase and τ_2 increases on increasing M. Table 1 displays also that τ_1 and τ_2 increase when Du, Sr, m and K increase. It is studies in table 2 that Nusselt number Nu increases on increasing Du and Sr, decreases on increasing Sc on the other hand Sherwood number Sh decreases when Du and Sr increase while Sh increases as Sc increases.

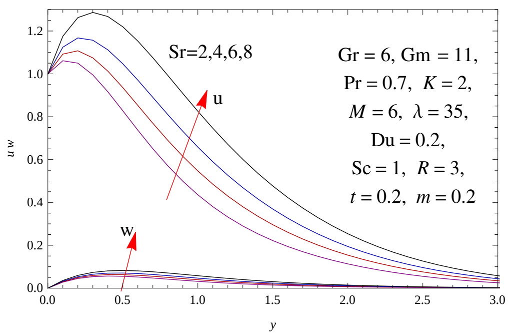

Figure 1. Velocity Profile for Different Values of Sr

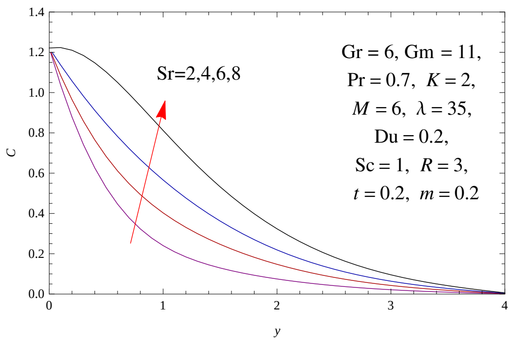

Figure 2. Concentration Profile for Different Values of Sr

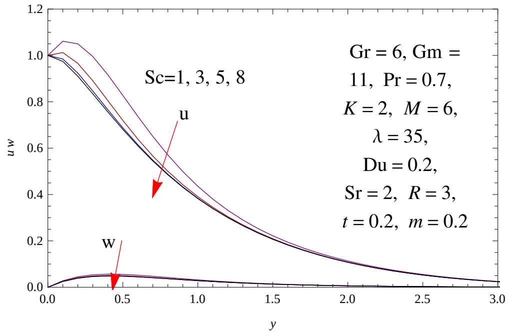

FIGURE 3. Velocity Profile for Different Values of Sc

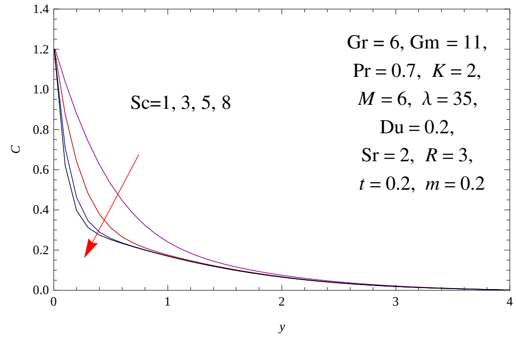

FIGURE 4. Concentration Profile for Different Values of Sc

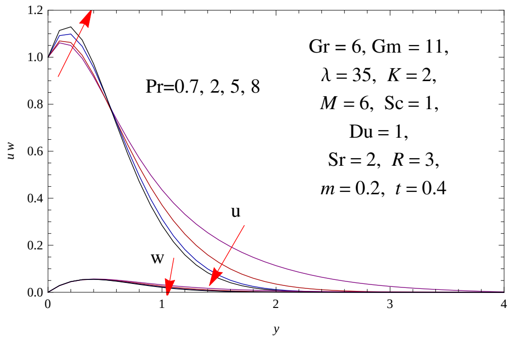

FIGURE 5. Velocity Profile for Different Values of Pr

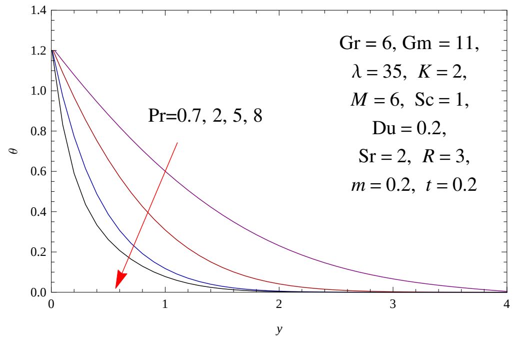

FIGURE 6. Temperature Profile for Different Values of Pr

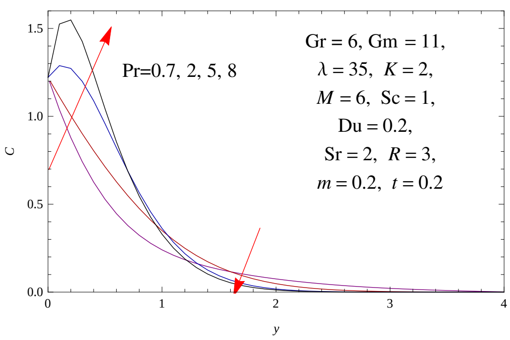

FIGURE 7. Concentration Profile for Different Values of Pr

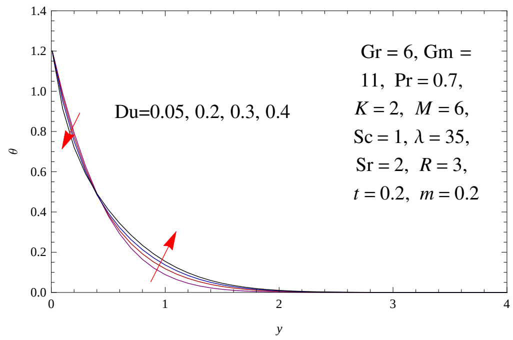

FIGURE 8. Temperature Profile for Different Values of Du

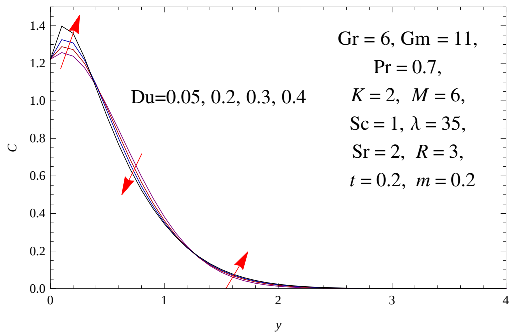

FIGURE 9. Concentration Profile for Different Values of Du

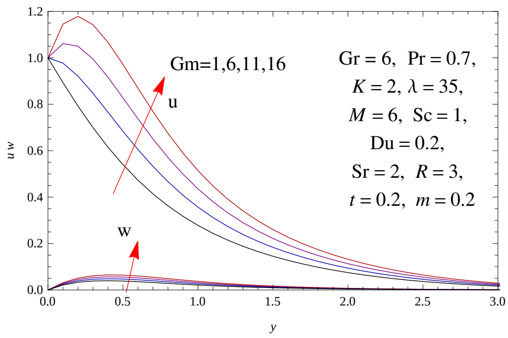

FIGURE 10. Velocity Profile for Different Values of Gm

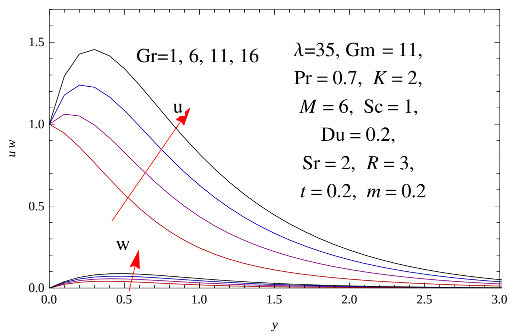

FIGURE 11. Velocity Profile for Different Values of Gr

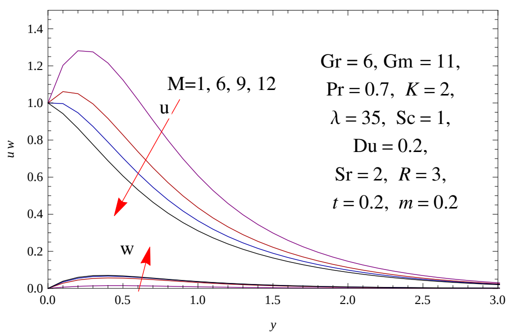

FIGURE 12. Velocity Profile for Different Values of M

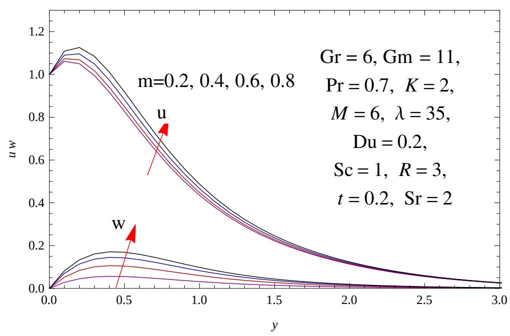

FIGURE 13. Velocity Profile for Different Values of m

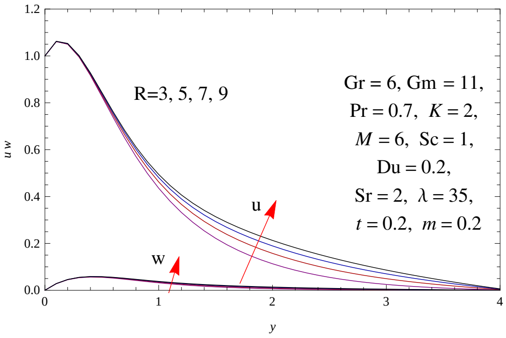

FIGURE 14. Velocity Profile for Different Values of R

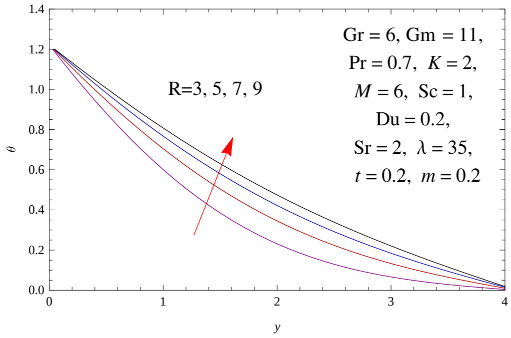

FIGURE 15. Temperature Profile for Different Values of R

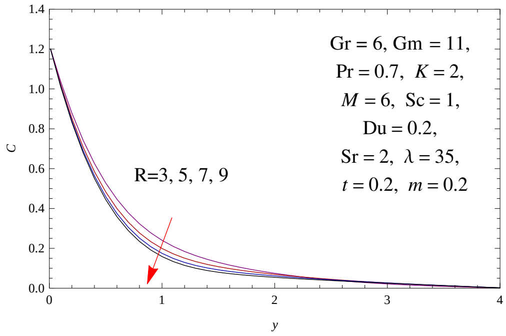

FIGURE 16. Concentration Profile for Different Values of R

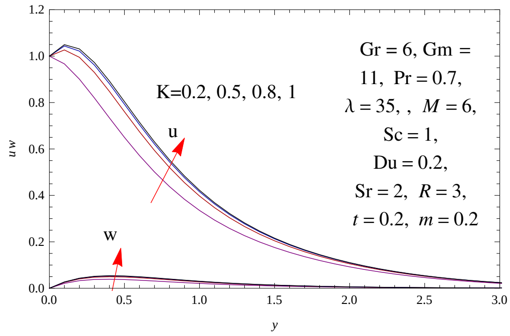

FIGURE 17. Velocity Profile for Different Values of K

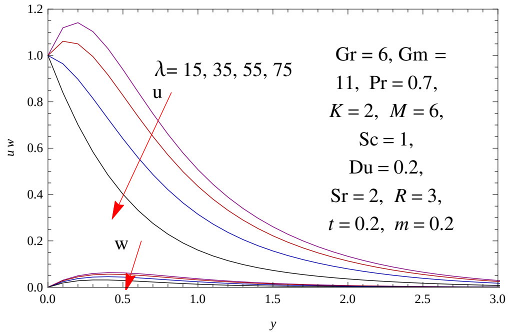

FIGURE 18. Velocity Profile for Different Values of λ

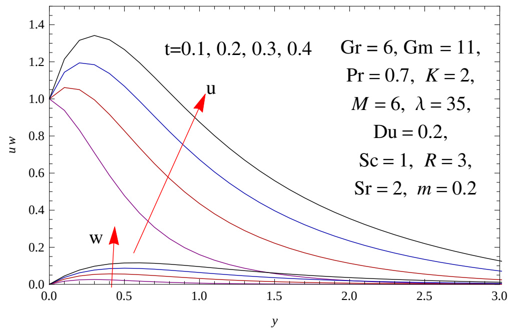

FIGURE 19. Velocity Profile for Different Values of t

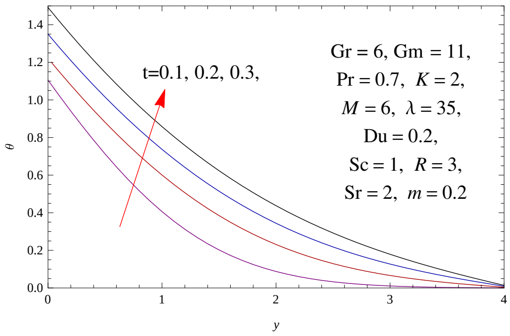

FIGURE 20. Temperature Profile for Different Values of t

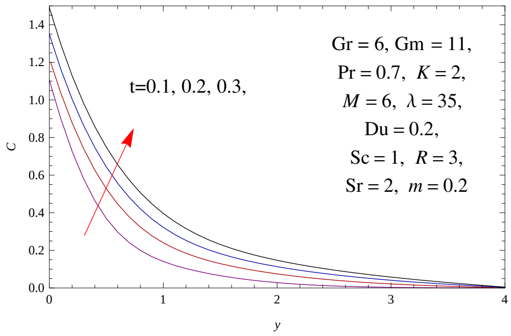

FIGURE 21. Concentration Profile for Different Values of t

TABLE 1. Skin friction coefficients τ_1 and τ_2 for different values of parameters

Du	K	M	m	Sc	Sr	λ	τ_1	τ_2
0.05	2	6	0.2	1	2	35	0.894201	0.282843
0.2	2	6	0.2	1	2	35	0.919244	0.283318
0.3	2	6	0.2	1	2	35	0.943915	0.28368
0.4	2	6	0.2	1	2	35	0.981835	0.28409
0.2	0.2	6	0.2	1	2	35	−0.333272	0.210789
0.2	0.5	6	0.2	1	2	35	0.266596	0.254016
0.2	0.8	6	0.2	1	2	35	0.43536	0.26696
0.2	1	6	0.2	1	2	35	0.49352	0.27155
0.2	2	1	0.2	1	2	35	2.03011	0.0674151
0.2	2	9	0.2	1	2	35	−0.0346252	0.348133
0.2	2	12	0.2	1	2	35	−0.575305	0.39051
0.2	2	6	0.4	1	2	35	0.734414	0.52343
0.2	2	6	0.6	1	2	35	0.903731	0.704545
0.2	2	6	0.8	1	2	35	1.08976	0.821369
0.2	2	6	0.2	3	2	35	0.123565	0.25864
0.2	2	6	0.2	6	2	35	−0.155025	0.249682
0.2	2	6	0.2	8	2	35	−0.257901	0.247028
0.2	2	6	0.2	1	4	35	0.922489	0.302472
0.2	2	6	0.2	1	6	35	1.24545	0.324496
0.2	2	6	0.2	1	9	35	1.75797	0.358691
0.2	2	6	0.2	1	2	15	1.19466	0.306231
0.2	2	6	0.2	1	2	55	−0.360621	0.238835
0.2	2	6	0.2	1	2	75	−1.60833	0.184768

TABLE 2. Nusselt number Nu and Sherwood number Sh for different values of parameters

Du	K	M	m	Sc	Sr	λ	Nu	Sh
0.05	2	6	0.2	1	2	35	2.31477	−0.356654
0.2	2	6	0.2	1	2	35	2.48536	−0.671419
0.3	2	6	0.2	1	2	35	2.6906	−1.04464
0.4	2	6	0.2	1	2	35	3.0872	−1.76321
0.2	2	6	0.2	3	2	35	0.68002	3.44431
0.2	2	6	0.2	6	2	35	0.634183	5.12367
0.2	2	6	0.2	8	2	35	0.610059	6.00334
0.2	2	6	0.2	1	4	35	0.735019	1.35892
0.2	2	6	0.2	1	6	35	0.747922	0.843116
0.2	2	6	0.2	1	9	35	0.769676	−0.0196965

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