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Combined effects of Soret-Dufour, Radiation and Chemical reaction on Unsteady MHD flow of Dusty fluid over inclined porous plate embedded in porous medium

Research Article

N. Pandya, Ravi Kant Yadav*, A.K. Shukla

Department of mathematics and astronomy, University of Lucknow, Lucknow-226007, India

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Abstract: The objective of this paper is to investigate effects of Soret-Dufour, radiation and chemical reaction on an unsteady MHD (Magnetohydro Dynamics) flow of an incompressible viscous and electrically conducting dusty fluid past a continuously moving inclined plate. Partial differential equations of non-dimensional form of governing equations of flow have been solved numerically using Crank-Nicolson implicit finite difference method. The effects of different physical parameters on velocity, temperature and concentration profiles are discussed with graphs and numerical values of skin friction coefficients, Nusselt number and Sherwood number are discussed with tables.

MSC: 76W05 • 76R50 • 78A40 • 76M20 • 80A32

Keywords: MHD • Chemical reaction • thermal radiation • porous medium • Heat and mass transfer • Crank-Nicolson method

1. Introduction

The study of magnetohydrodynamics of dusty fluid is motivated by its practical application in engineering. Among the application of MHD flow in porous media to engineering disciplines, one can find the food processing industry, chemical process industry and rotating machinery. The hydrodynamics flow of dusty fluid has been studied by number of research workers. Gebhart [1] considered the transient natural convection from vertical elements. Radiation effects on mixed convection along a vertical plate with uniform surface temperature were studied by Hossain and Takhar [3].

N. Pandya and A. K. Shukla[6] analyzed Soret-Dufour and Radiation Effects on Unsteady MHD Flow past an Impulsively Started Inclined Porous Plate with Variable Temperature and Mass Diffusion. N. Pandya and A. K. Shukla [7] has been studied Soret-Dufour and radiation effect on unsteady MHD flow over an inclined porous plate embedded in porous medium with viscous dissipation. Sparrow and Cess[2] have discussed the effect of magnetic field on free convection heat transfer. Rajesh et al.[4] analyzed effects of radiation and mass transfer on MHD flow with exponentially accelerated vertical plate. Bestman et al.[5] investigated interaction of mixed convection with thermal radiation in laminar flow.

Dubey et. al. [9] have analyzed on effect of the dusty viscous fluid on unsteady free convective flow along a porous hot vertical plate with thermal diffusion and mass transfer solved by perturbation techniques. Dubey et. al. [10] have studied effect of dusty viscous fluid on unsteady laminar free convective flow through porous medium along a

* Corresponding author.

E-mail address: ravikant.yadav31@gmail.com (Ravi Kant Yadav).

moving porous hot vertical plate with thermal diffusion. Recently, N. Pandya and Ravi Kant Yadav [8] has discussed Soret-Dufour effects on unsteady MHD flow of dusty fluid over inclined porous plate embedded in porous medium.

The objective of this research work is to study combined effects of Soret-Dufour, radiation and chemcial reaction on unsteady MHD flow of dusty fluid past an inclined porous plate embedded in porous medium variable temperature and mass diffusion. Nondimensional Partial differential equations of governing equations of flow field have been solved using Crank-Nicolson implicit finite difference method. Effects of different physical parameters of flow field on velocity, temperature, concentration, coefficients of skin-friction, Nusselt number and Sherwood number have been discussed through graphs and tables.

2. Mathematical Analysis

An unsteady MHD flow of a viscous incompressible dusty fluid past an infinite inclined plate with variable temperature and mass diffusion with radiation and chemical reaction has been analyzed. The plate is inclined at angle λ to vertical and embedded in porous medium. x'-axis has been considered along plate, y'-axis normal to it. A uniform magnetic field B_0 is taken along y'-axis and plate is electrically non-conducting. Magnetic Reynolds number and transversely applied magnetic file are very small so induced magnetic field is negligible in comparison to applied magnetic field, Cowling[11].

Due to infinite length in x' direction, flow variables are function of t' and y' only. Consider usual Boussinesq approximation, governing equations of flow field are:

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

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty)\,cos(\lambda) + g\beta^*(C' - C'_\infty)\,cos(\lambda) - \frac{\sigma B_0^2}{\rho}u' - \frac{\nu u'}{K'} + \frac{KN_0}{\rho}(V - u') \tag{2}$$

$$m_1\frac{\partial V}{\partial t'} = K(u' - V) \tag{3}$$

$$\rho C_p\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + \frac{\rho D_m K_T}{c_s}\frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D_m\frac{\partial^2 C'}{\partial y'^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T'}{\partial y'^2} - K_r(C' - C'_\infty) \tag{5}$$

where β^* is coefficient of volume expansion for mass transfer, β is volumetric coefficient of thermal expansion, v' is velocity along y'-axis, K is permeability of porous medium, σ is electrical conductivity, D_m is molecular diffusivity, g is acceleration due to gravity, K_T is thermal diffusion ratio, μ is viscosity, ρ is fluid density, k is thermal conductivity of fluid, C' and T' are dimensional concentration and temperature, V is the velocity of dust particles, C'_∞ and T'_∞ are concentration and temperature of free stream, q_r is radiative heat flux along y'-axis,N_0 is the number density of the dust particles which is taken to be constant, K is the stokeâĂŹs resistance coefficient,m_1 is the mass of dust particles, K_r is chemical reaction parameter, ν is kinematic viscosity and T_m is mean fluid temperature.

Boundary and initial conditional for this model are given as:

$$\begin{aligned}
&t' \leqslant 0 \quad u' = 0 \quad T' = T'_\infty \quad C' = C'_\infty \quad \forall y' \\
&t' > 0 \quad u' = u_0 \quad v' = -v_0 \\
&\qquad T' = T'_\infty + (T'_w - T'_\infty)e^{-At'}, \\
&\qquad C' = C'_\infty + (C'_w - C'_\infty)e^{-At'} \quad \text{at } y' = 0 \\
&\qquad u' = 0 \quad T' \to T'_\infty \quad C' \to C'_\infty \quad y' \to \infty
\end{aligned} \tag{6}$$

where T'_w and C'_w are concentration and temperature respectively of plate and $A = \frac{v_0^2}{\nu}$.

$$q_r = -\frac{4\sigma}{3k_m}\frac{\partial T'^4}{\partial y'} \tag{7}$$

where σ and k_m are Stefan Boltzmann constant and mean absorption coefficient respectively. in this model temperature difference within flow is very small, so that T'^4 may be expressed linearly with temperature. It is observed by expanding in a Taylor's series about T'_∞ and considering negligible higher order term, hence

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \tag{8}$$

so, by Eq. (7) and (8), Eq. (4) is reduced

$$\rho C_p \left(\frac{\partial T'}{\partial t'} + v' \frac{\partial T'}{\partial y'} \right) = k \frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma T'^3_\infty}{3k_m} \frac{\partial^2 T'}{\partial y'^2} + \frac{\rho D_m K_T}{c_s} \frac{\partial^2 C'}{\partial y'^2} \tag{9}$$

In order to obtain dimensionless partial differential equations, we introduce following quantities:

$$\begin{aligned}
&u = \frac{u'}{u_0}, \quad t = \frac{t' v_0^2}{\nu}, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Gm = \frac{\nu g \alpha^* (C'_w - C'_\infty)}{u_0 v_0^2},\\
&Gr = \frac{\nu g \alpha (T'_w - T'_\infty)}{u_0 v_0^2}, \quad Du = \frac{D_m K_T (C'_w - C'_\infty)}{c_s c_p \nu (T'_w - T'_\infty)}, \quad Sr = \frac{D_m K_T (T'_w - T'_\infty)}{T_m \nu (C'_w - C'_\infty)},\\
&K = \frac{v_0^2 K'}{\nu^2,}, \quad Pr = \frac{\mu c_p}{k}, \quad M = \frac{\sigma B_0^2 \nu}{\rho v_0^2},\\
&R = \frac{4\sigma T'^3_\infty}{k_m k}, \quad Sc = \frac{\nu}{D_m}, \quad y = \frac{y' v_0}{\nu},\\
&Ec = \frac{u_0^2}{c_p (T'_w - T'_\infty)}, \quad k_r = \frac{K_r \lambda}{v_0^2},\\
&v = \frac{V}{u_0}, \quad B_1 = \frac{\nu K N_0}{\rho u_0^2}, \quad B = \frac{m_1 u_0^2}{VK}
\end{aligned} \tag{10}$$

Using quantities of Eq. (10), we get non-dimensional form of Eqs. (2), (3), (9) and (5) respectively:

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\, cos(\lambda)\, \theta + Gm\, cos(\lambda)\, C + B_1 (v - u) - \left(M + \frac{1}{K} \right) u \tag{11}$$

$$B \frac{\partial v}{\partial t} = u - v \tag{12}$$

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{Pr} \left(1 + \frac{4R}{3} \right) \frac{\partial^2 \theta}{\partial y^2} + Du \frac{\partial^2 C}{\partial y^2} \tag{13}$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{Sc} \frac{\partial^2 C}{\partial y^2} + Sr \frac{\partial^2 \theta}{\partial y^2} - k_r C \tag{14}$$

dimensionless boundary and initial conditions are::

$$\begin{aligned}
&t \le 0 \quad u = 0 \quad \theta = 0 \quad C = 0 \quad \forall\, y\\
&t > 0 \quad u = 1\\
&\theta = e^{-t} \quad C = e^{-t} \quad at\; y = 0\\
&u = 0 \quad \theta \to 0 \quad C \to 0 \quad y \to \infty
\end{aligned} \tag{15}$$

Further, there is primary interest for research workers to calculate physical quantities skin-friction coefficients τ along wall x-axis, Nusselt number Nu and Sherwood number Sh. Non-dimensional form of these physical quantities are:

$$\begin{aligned}
\tau &= \left(\frac{\partial u}{\partial y} \right)_{y=0}\\
Nu &= -\left(\frac{\partial \theta}{\partial y} \right)_{y=0}\\
Sh &= -\left(\frac{\partial C}{\partial y} \right)_{y=0}
\end{aligned} \tag{16}$$

3. Method of Solution

Partial differential Eqs. (11) to (14) are solved with initial and boundary conditions (15). To find exact solution of these partial differential equations are impossible. So, these are solved numerically using Crank-Nicolson implicit finite difference method. First, Eqs. (11), (12), (13) and (14) are expressed as:

$$\begin{aligned} &\frac{u_{i,j+1}-u_{i,j}}{\Delta t}-\frac{u_{i+1,j}-u_{i,j}}{\Delta y}= \\ &\left(\frac{u_{i-1,j}-2u_{i,j}+u_{i+1,j}-2u_{i,j+1}+u_{i+1,j+1}}{2(\Delta y)^2}\right) \\ &+Gr\,cos(\lambda)\left(\frac{\theta_{i,j+1}+\theta_{i,j}}{2}\right)+Gm\,cos(\lambda)\left(\frac{C_{i,j+1}+C_{i,j}}{2}\right) \\ &+B_1\left(\left(\frac{v_{i,j+1}+v_{i,j}}{2}\right)-\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right)\right) \\ &-\left(M+\frac{1}{K}\right)\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right) \end{aligned} \tag{17}$$

$$\begin{aligned} &B\frac{v_{i,j+1}-v_{i,j}}{\Delta t}= \\ &\left(\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right)-\left(\frac{v_{i,j+1}+v_{i,j}}{2}\right)\right) \end{aligned} \tag{18}$$

$$\begin{aligned} &\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t}-\frac{\theta_{i+1,j}-\theta_{i,j}}{\Delta y}= \\ &\left(\frac{1}{Pr}+\frac{4R}{3Pr}\right) \\ &\left(\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i-1,j}-2\theta_{i,j+1}+\theta_{i+1,j+1}}{2(\Delta y)^2}\right) \\ &+Du\left(\frac{C_{i-1,j}-2u_{i,j}+C_{i-1,j}-2C_{i,j+1}+C_{i+1,j+1}}{2(\Delta y)^2}\right) \end{aligned} \tag{19}$$

$$\begin{aligned} &\frac{C_{i,j+1}-C_{i,j}}{\Delta t}-\frac{C_{i+1,j}-C_{i,j}}{\Delta y}= \\ &\frac{1}{Sc}\left(\frac{C_{i-1,j}-2u_{i,j}+C_{i-1,j}-2C_{i,j+1}+C_{i+1,j+1}}{2(\Delta y)^2}\right) \\ &+Sr\left(\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i-1,j}-2\theta_{i,j+1}+\theta_{i+1,j+1}}{2(\Delta y)^2}\right) \\ &-k_r\left(\frac{C_{i,j+1}+C_{i,j}}{2}\right) \end{aligned} \tag{20}$$

initial and boundary conditions are also expressed as:

$$\begin{aligned} &u_{i,0}=0 \quad \theta_{i,0}=0 \quad C_{i,0}=0 \quad \forall\, i \\ &u_{0,j}=1 \quad \theta_{0,j}=e^{-j\Delta t} \quad C_{0,j}=e^{-j\Delta t} \\ &u_{N,j}=0 \quad \theta_{N,j}\to 0 \quad C_{N,j}\to 0 \end{aligned} \tag{21}$$

here index i refers to y, j refers to time t, $\Delta t = t_{j+1}-t_j$ and $\Delta y = y_{i+1}-y_i$. Known values of u, θ and C at t, we solved above equations for values $t+\Delta t$ as follows: We obtain these values to substitute $i = 1,2,3,\cdots,N-1$, where N pertains to ∞ then Eqs. (17) to (20) give tridiagonal system of equations with initial and boundary conditions in Eq. (21) are solved using Thomos algorithm as discussed in Carnahan et al.[12], we are found values of θ and C for all values of y at $t+\Delta t$. Eqs. (17) and (18) are solved by same to substitute these values of θ and C, we get solution for u till desired time t. calculation were execute for $\Delta y = 0.1$, $\Delta t = 0.001$ and repeated till $y = 4$.

4. Result and discussion

The following discussion brings out the effects of some pertinent parameters such as magnetic field parameter M, Dufour number Du, Soret number Sr, Schmidt number Sc, radiation parameter R, chemical reaction parameter kr, dusty fluid parameters B_1, dusty particle parameter B, and inclination angle λ. The numerical calculation carried out for fixed value of $Gr = 5$, $Gm = 10$, $K = 2$ and $Pr = 0.71$. The results have been expressed graphically for velocity profile u, temperature profile θ and concentration profile C.

Figs. 1 and 9 show that velocity u increases as Soret number Sr and Radiation parameter R increase respectively. On increasing Schmidt number Sc, velocity u and concentration C both decreases in Fig. 3 and Fig. 4 respectively. When Dufour number Du increases, concentration C and temperature θ increase in Figs. 5 and 6. Figs. 12, 13, 7 and 17 depict that velocity decreases as dusty fluid parameters B, dusty particle parameter B_1, chemical reaction parameter kr and inclination angle λ increase respectively. Temperature increases as Radiation parameter R and Dufour number Du increase in Figs. 10 and 6. Fig. 8 shows that concentration C increases and chemical reaction parameter kr increases.

In Fig. 11, concentration C first decreases after then increases as radiation parameter R increases. Fig. 15 shows that velocity u increases as time increases and in Figs. 14 and 16, it is clear that first temperature θ and concentration C decrease after then increase. From Table 1, it is clear that on increasing Dufour number, radiation parameter, chemical reaction parameter inclination angle, dusty fluid parameters, dusty particle parameter, and Schmidt number, skin-friction coefficient τ decreases. Further skin-friction coefficient τ increases as time and Soret number increase.

In Table 2, we have analyzed that Nusselt number Nu decreases and Sherwood number Sh increases as Dufour number, chemical reaction parameter, radiation parameter and Schmidt number increase. On other hand, Nusselt number increases and Sherwood number decreases when Soret number increases and both of them decrease as time increases.

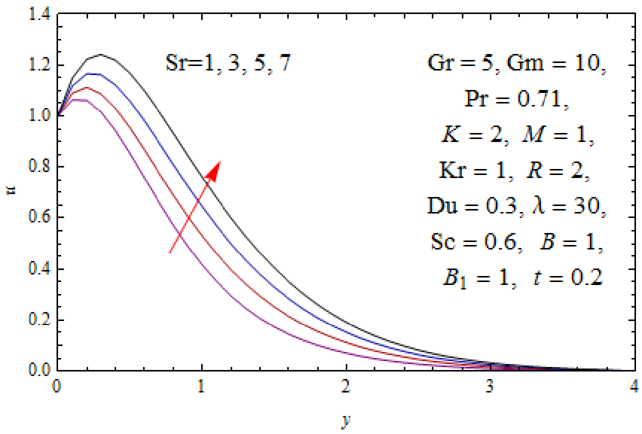

Fig. 1. Velocity Profile for Different Values of Sr

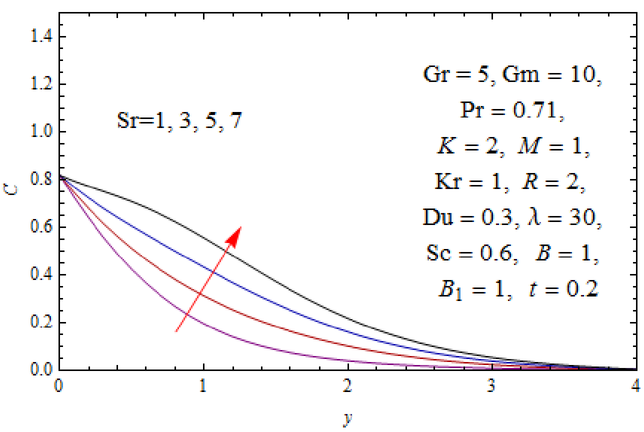

Fig. 2. Concentration Profile for Different Values of Sr

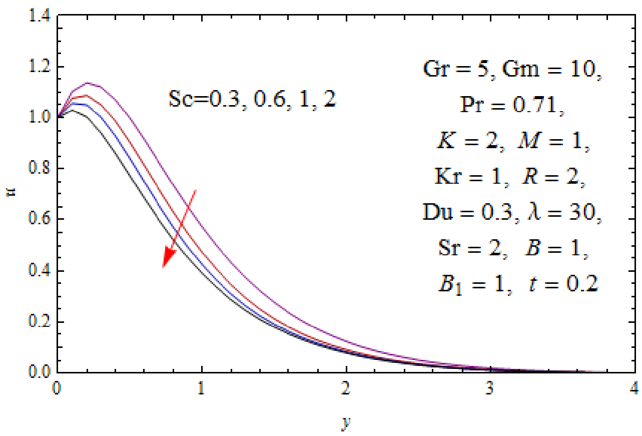

Fig. 3. Velocity Profile for Different Values of Sc

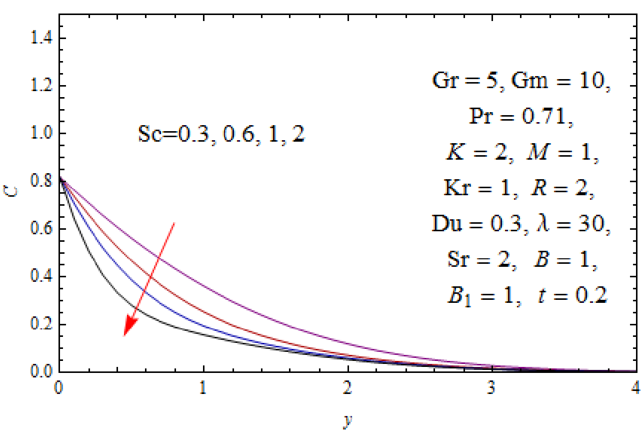

Fig. 4. Concentration Profile for Different Values of Sc

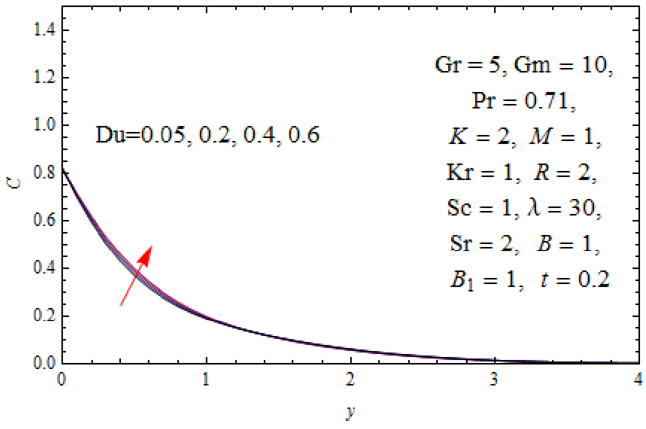

Fig. 5. Concentration Profile for Different Values of Du

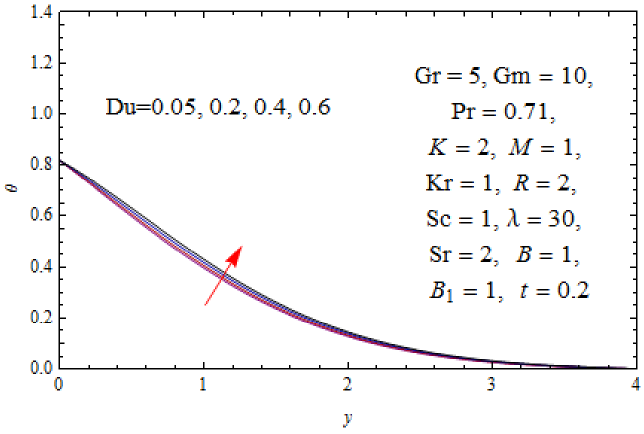

Fig. 6. Temperature Profile for Different Values of Du

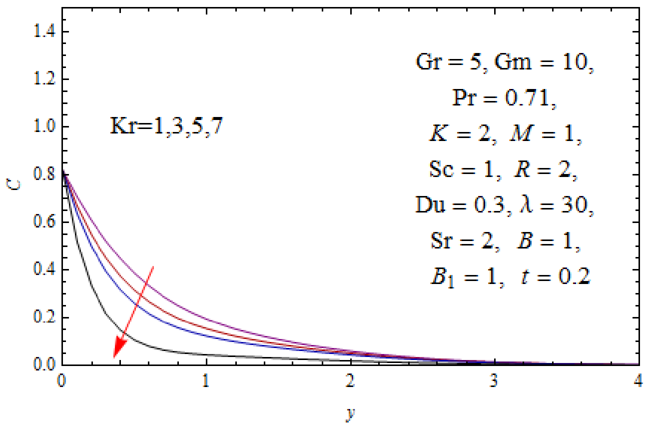

Fig. 7. Concentration Profile for Different Values of kr

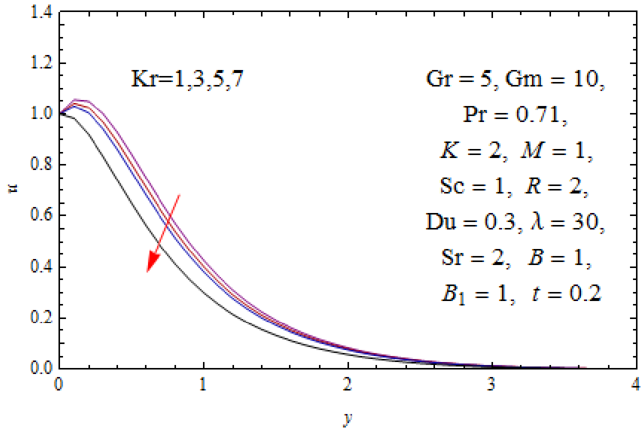

Fig. 8. Velocity Profile for Different Values of kr

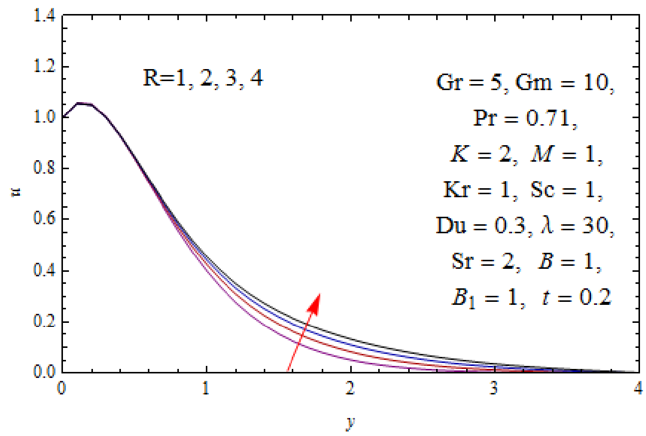

Fig. 9. Velocity Profile for Different Values of R

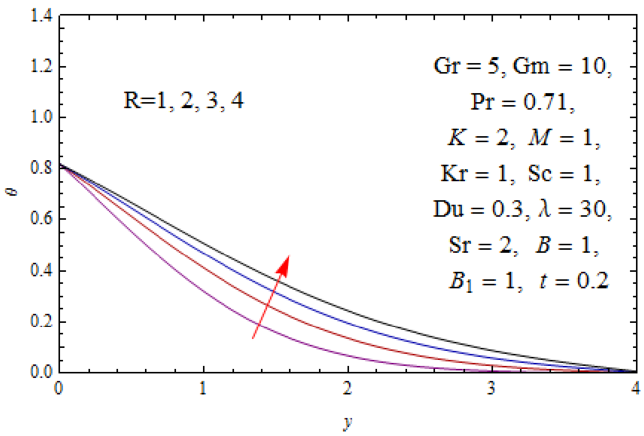

Fig. 10. Temperature Profile for Different Values of R

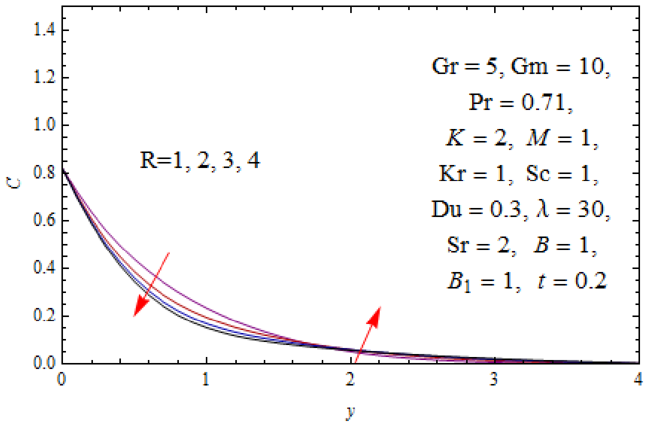

Fig. 11. Concentration Profile for Different Values of R

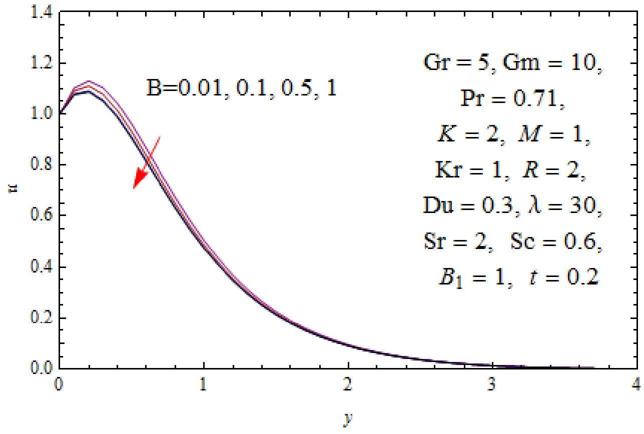

Fig. 12. Velocity Profile for Different Values of B

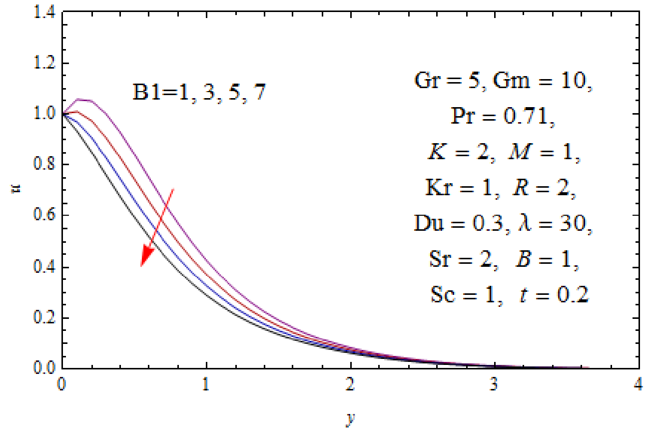

Fig. 13. Velocity Profile for Different Values of B_1

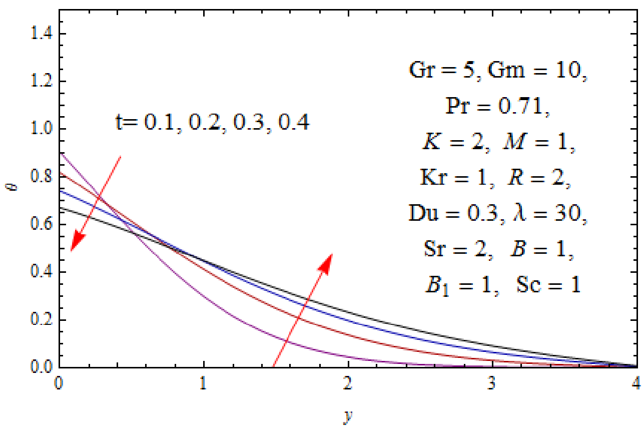

Fig. 14. Temperature Profile for Different Values of t

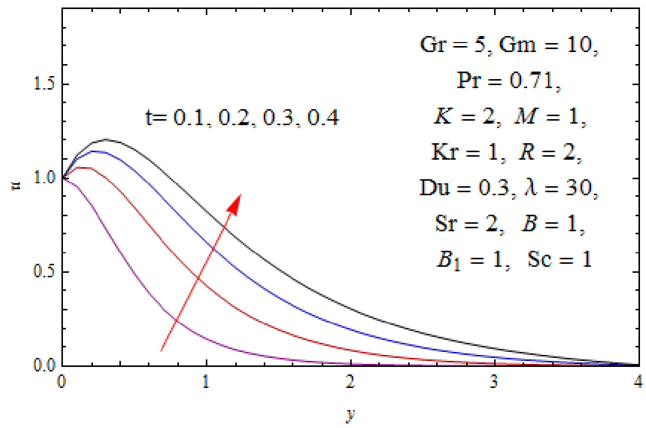

Fig. 15. Velocity Profile for Different Values of t

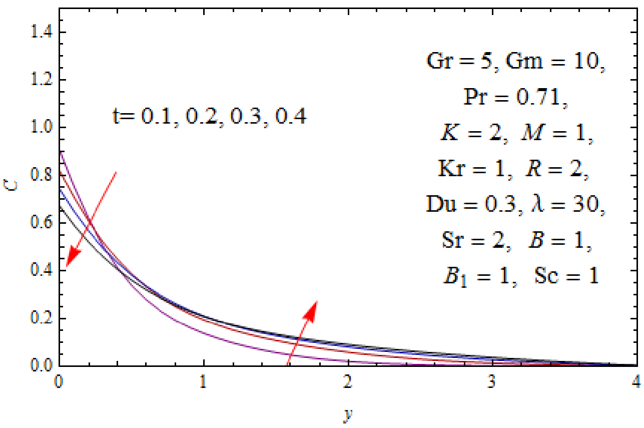

Fig. 16. Concentration Profile for Different Values of t

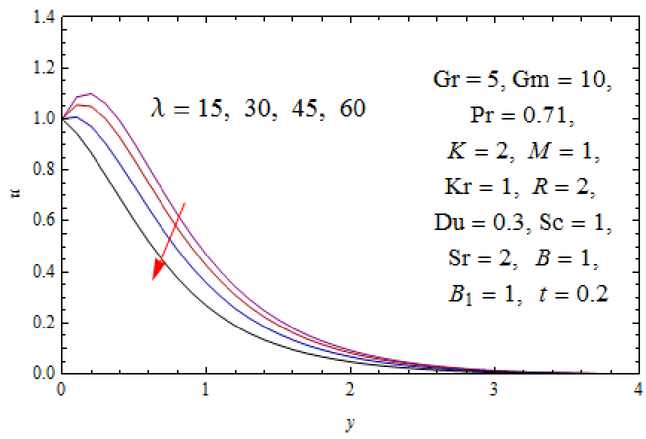

Fig. 17. Velocity Profile for Different Values of λ

Table 1. Skin friction coefficient τ for different values of parameters

t	kr	B	Sc	Sr	R	B_1	Du	λ	τ
0.1	1	1	1	2	2	1	0.3	30	−0.475593
0.3	1	1	1	2	2	1	0.3	30	1.02161
0.4	1	1	1	2	2	1	0.3	30	1.2251
0.2	3	1	1	2	2	1	0.3	30	0.424903
0.2	5	1	1	2	2	1	0.3	30	0.306442
0.2	7	1	1	2	2	1	0.3	30	−0.172543
0.2	1	0.01	0.6	2	2	1	0.3	30	1.02937
0.2	1	01	0.6	2	2	1	0.3	30	0.915588
0.2	1	0.5	0.6	2	2	1	0.3	30	0.793228
0.2	1	1	0.6	2	2	1	0.3	30	0.767257
0.2	1	1	0.3	2	2	1	0.3	30	1.03177
0.2	1	1	0.6	2	2	1	0.3	30	0.767257
0.2	1	1	2	2	2	1	0.3	30	0.295919
0.2	1	1	1	1	2	1	0.3	30	0.634525
0.2	1	1	1	3	2	1	0.3	30	0.903393
0.2	1	1	1	5	2	1	0.3	30	1.8673
0.2	1	1	1	7	2	1	0.3	30	1.4865
0.2	1	1	1	2	1	1	0.3	30	0.58862
0.2	1	1	1	2	3	1	0.3	30	0.56302
0.2	1	1	1	2	4	1	0.3	30	0.565268
0.2	1	1	1	2	2	3	0.3	30	0.0944833
0.2	1	1	1	2	2	5	0.3	30	−0.314948
0.2	1	1	1	2	2	7	0.3	30	−0.673701
0.2	1	1	1	2	2	1	0.05	30	0.57572
0.2	1	1	1	2	2	1	0.2	30	0.570373
0.2	1	1	1	2	2	1	0.4	30	0.56403
0.2	1	1	1	2	2	1	0.6	30	0.553318
0.2	1	1	1	2	2	1	0.3	15	0.873231
0.2	1	1	1	2	2	1	0.3	45	0.0786036
0.2	1	1	1	2	2	1	0.3	60	−0.0557256

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

t	kr	B	Sc	Sr	R	B_1	Du	λ	Nu	Sh
0.1	1	1	1	2	2	1	0.3	30	0.665233	1.53647
0.3	1	1	1	2	2	1	0.3	30	0.265555	0.930193
0.4	1	1	1	2	2	1	0.3	30	0.184869	0.802387
0.2	3	1	1	2	2	1	0.3	30	0.37572	1.51058
0.2	5	1	1	2	2	1	0.3	30	0.358772	1.83055
0.2	7	1	1	2	2	1	0.3	30	0.292822	3.00238
0.2	1	1	0.3	2	2	1	0.3	30	0.4258834	0.561152
0.2	1	1	0.6	2	2	1	0.3	30	0.411797	0.82959
0.2	1	1	2	2	2	1	0.3	30	0.360044	1.76726
0.2	1	1	1	1	2	1	0.3	30	0.406703	0.927428
0.2	1	1	1	3	2	1	0.3	30	0.417189	0.726412
0.2	1	1	1	5	2	1	0.3	30	0.428993	0.501808
0.2	1	1	1	7	2	1	0.3	30	0.442417	0.248285
0.2	1	1	1	2	1	1	0.3	30	0.521461	0.977653
0.2	1	1	1	2	3	1	0.3	30	0.331187	1.19466
0.2	1	1	1	2	4	1	0.3	30	0.290526	1.2332
0.2	1	1	1	2	2	1	0.05	30	0.4385	1.06803
0.2	1	1	1	2	2	1	0.2	30	0.413475	1.10247
0.2	1	1	1	2	2	1	0.4	30	0.376728	1.15394
0.2	1	1	1	2	2	1	0.6	30	0.335303	1.21316

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