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MHD unsteady free convection boundary layer flow with dissipation and chemical reaction through a porous medium under slip boundary conditions

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Abstract
In the present paper chemical reaction effects as well as viscous heat dissipation on the transient free convection and mass transfer flow of an electrically conducting, viscous, incompressible fluid, past an infinite vertical porous plate, in presence of uniform externally applied transverse magnetic field. Moreover, at the plate there is slip for velocity field and jump in temperature field. The concentration is assumed to be oscillating with time. Adopting a perturb bative series expansion about a small parameter, $\in$, expression are obtained and are shown graphically describing the velocity, temperature, skin-friction coefficient and the rate of heat transfer. It is being observed that Nusselt number increase with increase in chemical reaction parameter.

Keywords: Chemical reaction, free convection, Heat mass transfer, MHD, Velocity slip, viscous dissipation

1. Introduction

Flow in a porous medium is one of the main topic of the periodic mass transfer to the chemically reacting MHD free convection on an infinite vertical plate. There are many transport processes, which occur naturally and artificially in which flow is modified or driven by density differences caused by temperature, chemical composition differences and gradients, and material or phase constitution.

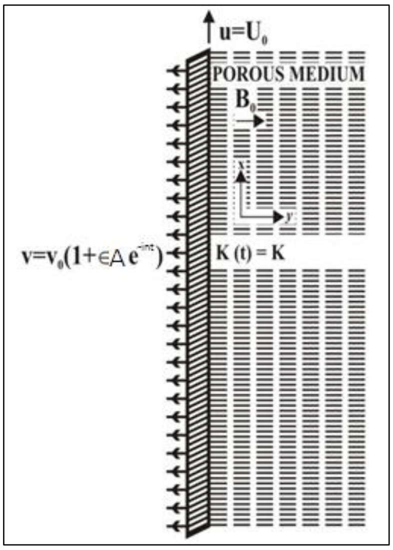
The great interest in this area stems from its rapid expanse and wide spread in several engineering, industrial, geophysical and astrophysical application. Such as polymer production, manufacturing of ceramic, packed-bed catalytic reactors, food processing, cooling of nuclear reactors, enhanced oil recovery, underground energy transport, magnetized plasma flow, high speed plasma wind, cosmic jets and stellar systems. A clear understanding of the nature of interaction between thermal and concentration buoyancies is necessary to control these processes. The problems of steady and unsteady combined heat and mass transfer by free convection along an infinite and semi-infinite vertical plate with and without chemical reaction have been studied extensively by different scholars. Reddy *et al.* [1] studied thermo diffusion and chemical effects with simultaneous thermal and mass diffusion in MHD mixed convection flow with Ohmic heating. Krishnendu [2] presented a mathematical model to analyze the steady boundary layer slip flow and mass transfer with nth order chemical reaction past a porous plate embedded in a Darcy porous medium. Bhattacharya and Layek [3] (2012) obtained similarity solution of MHD boundary layer flow with mass diffusion and chemical reaction over a porous flat plate with suction/blowing. Chamkha *et al.* [4] (2011) discussed the effects of Joule heating, chemical reaction and thermal radiation on unsteady hydro magnetic natural convection boundary layer flow with heat and mass transfer of a micro polar fluid from a semi-infinite heated vertical porous plate in the presence of a uniform transverse magnetic field. Gupta and Sharma [5] attended to study MHD flow of viscous fluid past a porous medium enclosed by an oscillating porous plate in slip flow regime. Ibrahim and Makinde [6] attended a study on chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate with suction.

Additionally, Gbadeyan and Dada [7] investigated radiation and heat transfer effects on MHD non-Newtonian unsteady flow in a porous medium with slip condition. The theoretical analysis of unsteady hydrodynamic free convective flow of a viscoelastic fluid past an infinite vertical porous channel through a porous medium was recently, investigated by Aarti and Gorla [8]. An analytic study of MHD free convective, dissipative oundary layer flow past a porous vertical surface in the presence ofthermal radiation, hemical reaction and constant suction was done by M.C. Raju *et al.* [9]. Mohamed *et al.* [10] (2013) investigated unsteady hydromagnetic natural convection flow with heat and mass transfer of a viscous, incompressible and electrically conducting and radiating fluid past through a porous medium near an impulsively moving hot vertical plate in the presence of homogeneous chemical reaction of first order and temperature dependent heat sink. Radiation and chemical reaction effects on an unsteady MHD convection lfow past a vertical moving porous palte embedded in a porous medium with viscous dissipation was studied by M. Sudheer Babu *et al.* [11]. Ahmed and Kishore [12] reported MHD mass transfer flow past a vertical porous plate embedded in a porous medium in a slip flow regime with thermal radiation and chemical reaction. Seshaiah *et al.* [13] analyzed the effects of chemical reaction and radiation on unsteady MHD free convective fluid flow embedded in a porous medium with time-dependent suction with temperature gradient heat source. Mohammed and Suneetha [14] discussed the effects of thermal diffusion and chemical reaction on MHD transient free convection flow past a porous vertical plate with radiation, temperature gradient heat source in slip flow regime. Most recently, Nityananda and Rajendra [15] examined the effect of slip condition on unsteady MHD oscillatory flow in a channel filled with saturated porous medium in the presence of transverse magnetic field and radiative heat and mass transfer. Chemical reaction and radiation absorption effects on free convection flow through porous medium with variable suction in the presence of uniform magnetic field was studied by Sudheer Babu and Satyanarayana [16].

2. Mathematical formulation of the problem

We consider the unsteady MHD free convection flow of an electrically conducting viscous in compressible fluid over a porous vertical infinite isothermal plate with homogeneous chemical reaction of first order. The plate to subjected to a variable suction velocity fluctuating with time and is defined as

$$v = -v_0 (1 + \in Ae^{int}) \tag{2.1}$$



The x-axis is assumed to be taken along the plate and the y-axis normal to the plate. Since the plate is considered infinite in x direction, hence all physical quantities will depend on y and t only. The plate is moving with constant velocity U_0 and maintained at constant temperature T_w and concentration C_w. Moreover, there is slip in velocity, jump in temperature and concentration is fluctuating at the plate. Also, it is assumed that there exists a homogeneous chemical reaction of first order with rate constant k between the diffusing species and the fluid. Boussinesq approximation, the governing equations for the problem under consideration are:

$$\frac{\partial u}{\partial t} - v_0\left(1 + \in Ae^{int}\right)\frac{\partial u}{\partial y} = g\beta(T - T_\infty) + g\beta^*(C - C_w) + \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\upsilon}{K}u - \frac{\sigma B_0^2 u}{\rho} \tag{2.2}$$

$$\frac{\partial T}{\partial t} - v_0\left(1 + \in Ae^{int}\right)\frac{\partial T}{\partial y} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} + \frac{\upsilon}{C_p}\left(\frac{\partial y}{\partial y}\right)^2 \tag{2.3}$$

$$\frac{\partial C}{\partial t} - v_0\left(1 + \in Ae^{int}\right)\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - k(C - C_\infty) \tag{2.4}$$

Where u and υ, are the components of velocity along x and y directions, σ is the electrical conductivity, A is suction parameter, n is frequency parameter, β and β^1 are coefficient of thermal expansion and thermal expansion with concentration respectively, D is the chemical molecular diffusivity, k is chemical reaction coefficient, υ is the kinematic viscosity. Remaining symbols have their usual meaning.
The boundary conditions are:

$$u = U_1 + L_1 \frac{\partial u}{\partial y}, \quad T = T_w + L_2 \frac{\partial T}{\partial y}, \quad C = C_w + (C_w - C_\infty) \in e^{int} \text{ at } y = 0$$

$$u \to 0, \quad T \to T_\infty, C \to C_\infty \quad \text{as } y \to \infty \tag{2.5}$$

where $L_1 = \left(\frac{2 - m_1}{m_1}\right) L,\ L_2 = \left(\frac{2 - a}{a}\right)\left(\frac{1.996\ \gamma}{\gamma + 1}\right)\frac{L}{P_r}$,

Here L is the mean free path, m_1 is the Maxwells reflection coefficient, a is the thermal accommodation coefficient and is gas constant.
We introducing the following non-dimensional quantities

$$u^* = \frac{u}{\nu_0},\quad y^* = \frac{\nu_0 y}{\upsilon},\quad n^* = \frac{4 n \upsilon}{\nu_0^2},\quad t^* = \frac{t \nu_0^2}{4\upsilon},\quad T = \frac{T - T_\infty}{T_w - T_\infty},\quad \theta = \frac{C - C_\infty}{C_w - C_\infty}$$

$k^* = \frac{k\upsilon}{\nu_0^2}$ (Chemical Reaction parameter), $K^* = \frac{K \nu_0^2}{\upsilon^2}$ (Permeability parameter)

$S_c = \frac{\nu}{D}$ (Schmidt number), $M^2 = \frac{\sigma \mu_e B_0^2 \nu_0}{\rho \nu_0^2}$ (Magnetic field parameter),

$Gr = \frac{\upsilon g \beta (T_w - T_\infty)}{\nu_0^3}$ (Grashoff number),

$Gr = \frac{\upsilon g \beta^* (C_w - C_\infty)}{\nu_0^3}$ (Grashoff number of mass transfer),

$Pr = \frac{\mu C_p}{k_0}$ (Prandtl number), $Ec = \frac{\nu_0^2}{C_p (T_w - T_\infty)}$ (Eckart number)

$\alpha^* = \frac{U_0}{\nu_0}$ (Plate velocity parameter), $h_1 = \frac{L_1 \nu_0}{\upsilon}$ (Velocity slip parameter)

$h_2 = \frac{L 2 \nu_0}{\upsilon}$ (Temperature jump parameter)

In equations (2.2), (2.4) and get the following form after ropping the asterisk over them.

$$\frac{1}{4}\frac{\partial u}{\partial t} - \left(1 + \in Ae^{int}\right)\frac{\partial u}{\partial y} = GrT + Gc\,\phi + \frac{\partial^2 u}{\partial y^2} - \left(M^2 + \frac{1}{K}\right)u \tag{2.6}$$

$$\frac{1}{4}\frac{\partial T}{\partial t} - \left(1+\in Ae^{int}\right)\frac{\partial T}{\partial y} = \frac{1}{Pr}\frac{\partial^2 T}{\partial y^2} + Ec\left(\frac{\partial y}{\partial y}\right)^2 \quad (2.7)$$

$$\frac{1}{4}\frac{\partial \phi}{\partial t} - \left(1+\in Ae^{int}\right)\frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - k\phi \quad (2.8)$$

The corresponding boundary conditions as:

$$u = \alpha + h_1\frac{\partial u}{\partial y},\ \ T = 1 + h_1\frac{\partial T}{\partial y},\ \ \phi = 1+\in e^{int} \text{ at } y = 0$$

$$u\to 1,\ T\to 0,\ \phi\to 0, \text{ as } y\to\infty \quad (2.9)$$

3. Solution of the problem

To the solve equations (2.6) to (2.8), we follows the perturbation technique in the form ($\in$<<1)

$u = u_0 (y) + \in e^{int} u_1(y) + 0 (t^2)$ (3.1)

$T = T_0 (y) + \in e^{int} T_1(y) + 0 (t^2)$ (3.2)

$\phi = \phi_0 (y) + \in e^{int}\phi_1(y) + 0 (t^2)$ (3.3)

Substitution of equations (3.1) to (3.3) in equations (2.6) to (2.8) and equating the coefficient of like powers of $\in$ (neglecting $\in^2$ etc.), we obtain the following set of differential equations.

$$\frac{d^2u_0}{dy^2} + \frac{du_0}{dy} - \left(M^2 - \frac{1}{K}\right)u_0 = -G_rT_0 - G_c\phi_0 \quad (3.4)$$

$$\frac{d^2u_1}{dy^2} + \frac{du_1}{dy} - \left(M^2 + \frac{in}{4}\frac{1}{K}\right)u_1 = -G_rT_1 - G_c\phi_1 - A\frac{du_0}{dy} \quad (3.5)$$

$$\frac{d^2T_0}{dy^2} + \frac{dT_0}{dy} = -P_rE_c\left(\frac{du_0}{dy}\right)^2 \quad (3.6)$$

$$\frac{d^2T_1}{dy^2} + P_r\frac{dT_1}{dy} - \frac{in}{4}P_rT_1 = -AP_r\frac{dT_0}{dy} - 2P_rE_c\left(\frac{du_0}{dy}\right)\left(\frac{du_1}{dy}\right) \quad (3.7)$$

$$\frac{d^2\phi_0}{dy^2} + \frac{d\phi_0}{dy} - kS_c\phi_0 = 0 \quad (3.8)$$

$$\frac{d^2\phi_0}{dy^2} + \frac{d\phi_0}{dy} - kS_c\phi_0 = 0 \quad (3.9)$$

The corresponding boundary conditions are:

$$u = \alpha + h_1\frac{du_0}{\partial y},\ \ u_1 = h_1\frac{du_1}{dy},\ \ T_0 = 1 + h_2\frac{dT_0}{dy},\ \ T_0 = h_2\frac{dT_1}{dy},\ \text{At } y = 0$$

$$u_0\to 0,\ u_1\to 0,\ T_0\to 0,\ T_1\to 0,\ \phi_0\to 0,\ \phi_1\to 0, \quad \text{as } y\to\infty \quad (3.10)$$

The none-linear terms in equation (3.4) to (3.9) are multiplied by E_c in order to deCouple them, since it, is known that E_c<< 1 for all incompressible fluids, it is assumed that

$u_0(y) = u_{00}(y) + E_c u_{01}(y)$, $u1(y) = u_{10}(y) + E_c u_{11}(y)$
$T_0(y) = T_{00}(y) + E_c T_{01}(y)$, $T1(y) = T_{10}(y) + E_c T_{11}(y)$
$\phi_0(y) = \phi_{00}(y) + E_c\phi_{01}(y)$, $\phi_1(y) = \phi_{10}(y) + E_c\phi_{11}(y)$ (3.11)

Substituting equations (3.11) into equation (3.4) to (3.10) and with convection that the real parts of complex quantities have physical significance in the problem so using equations (3.1) to (3.3), the velocity, temperature and concentration field can be expressed in fluctuating parts as

$U(y,t) = u_0(y) + \in (F_r\cos nt - F_i \sin nt)$ (3.12)
$T(y,t) = T_0(y) + \in (H_r\cos nt - H_i\text{innt})$ (3.13)
$\phi(y,t) = \phi_0(y) + \in (S_r\cos nt - S_i \sin nt)$ (3.14)

Where $F_r + {}_iF_i = u_1(y)$, $H_r + {}_iH_i = T_1(y)$, $Sr + {}_iS_i = \phi_1(y)$

Hence expression for transient velocity, temperature and concentration field for $nt = \frac{\pi}{2}$ are

$$u\left(y_1 \frac{\pi}{2n}\right) = u_0(y) - \in F_i \quad (3.15)$$

$$T\left(y_1 \frac{\pi}{2n}\right) = T_0(y) - \in H_i \quad (3.16)$$

$$\phi\left(y_1 \frac{\pi}{2n}\right) = \phi_0(y) - \in S_i \quad (3.17)$$

4. Skin Friction

Important parameter in non-dimensional form namely skin friction, at the plate y = 0, is

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$\tau = \left(\frac{\partial u_0}{\partial y}\right)_{y=0} + \in |J| \mathrm{Cos}\,(nt + \psi_1)$$

$$\tau = \tau_1 + \in |J| \mathrm{Cos}\,(nt + \psi_1) \quad (4.1)$$

Where

$$J = J_r + {}_iJ_i = \left(\frac{\partial u_1}{\partial y}\right)_{y=0} \quad \tan \psi_1 = \frac{j_1}{J_r}$$

$$\tau_1 = -m_3H_3 + \Pr H_1 + m_1H_2 + Ec\left[-m_3H_{11} + \Pr H_4 - 2\Pr H_5 - 2m_1H_6\right.$$

$$\left. - 2m_3H_7 - m_4H_8 + m_5H_9 + m_6H_{10}\right]$$

5. Nusselt Number

Another important parameter in non-dimensional form namely Nusselt number, at the plate y=0, is

$$Nu = -h_1 \left(\frac{\partial T}{\partial y} \right)_{y=0}$$

$$Nu = -h_1 \left(\frac{\partial T_0}{\partial y} \right)_{y=0} + \in |E| Cos\ (nt + \psi_2)$$

$$Nu = -h_1 Nu_1 - \in h_1 |E| Cos\ (nt + \psi_1)$$

$$Nu = q_1 \in h_1 |E| Cos\ (nt + \psi_1) \tag{5.1}$$

Where

$$E = E_r + {}_i E_i = \left(\frac{\partial T_1}{\partial y} \right)_{y=0} \quad \tan \psi_2 = \frac{E_1}{E_r}$$

And the sinusoidal Nusselt number

$$q_1 = -h_1 \left[-Pr\ R_1 + Ec \left\{ -Pr\ q_7 + 2\ Pr\ q_1 + 2 m_1 q_2 + 2 m_3 q_3 + m_4 q_4 \right.\right.$$

$$\left.\left. - m_5 q_5 - m_6 q_6 \right\} \right]$$

6. Results and discussion

In table 3.1, the amplitude of skin friction |J| is observed to be increasing with increase in k_1, h_1, A and S_c where as it decreases on increasing M andh_2. The values for pase angle of the skin friction (tan ψ_1) are also obtained in table, for different parameters entering into the problem.

Table 3.1: Dimensionless shearing stress in terms of amplitude I J and phasetan φ_1, $(n = 0.1, \in 0.02, K = 5.0, P_r = 0.71, G_r = 5.0, G_c = 0.6, E_c = 0.01\ and\ nt = \frac{\pi}{2}, \propto = 0.1)$

Sr. no	M	K	h_1	k_1	A	S_c	|J|	tan φ_1
1	1.0	0.5	0.05	0.1	1	0.30	4.32635	1.21315
2	0.5	0.5	0.05	0.1	1	0.30	6.12468	1.65413
3	1.0	0.5	0.05	0.1	1	0.30	28.28443	0.65812
4	1.0	0.5	0.1	0.1	1	0.30	0.30992	1.91482
5	1.0	0.5	0.05	0.1	1	0.30	6.21192	1.01282
6	1.0	0.5	0.05	0.1	5	0.30	7.32618	2.10821
7	1.0	0.5	0.1	0.1	1	0.30	12.13547	0.71351
8	1.0	0.5	0.1	0.1	1	0.30	28.04342	0.59213

The amplitude of rate of heat transfer |E| is observed through Table 3.2. We notice that |E| increases with increase in $M, k, h_1\ A$ and S_c and it drops with increase in h_2. The values for phase angle of the rate of heat transfer (tan ψ_2) are also obtained in table, for the different parameters.

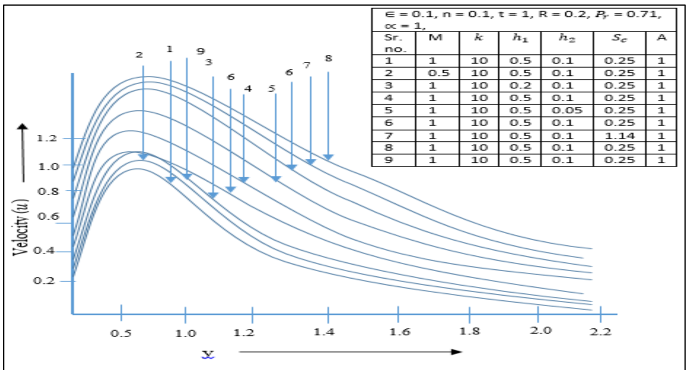
Table 3.2: Rate of heat transfer in terms of amplitude |E| and phasetan φ_1 $(n = 0.1, \in 0.02, K = 5.0, P_r = 0.71, G_r = 5.0, G_c = 0.6, E_c = 0.01\ and\ nt = \frac{\pi}{2}, a = 0.1)$

Sr. no	M	K	h_1	k_1	A	S_c	| E |	tan φ_1
1	1.0	0.5	0.05	0.1	1	0.30	2.73482	0.78385
2	0.5	0.5	0.05	0.1	1	0.30	1.89335	0.35982
3	1.0	2.0	0.05	0.1	1	0.30	4.81582	1.12591
4	1.0	0.5	0.1	0.1	1	0.30	2.85159	0.38393
5	1.0	0.5	0.05	0.05	1	0.30	3.85891	0.03893
6	1.0	0.5	0.05	0.1	5	0.30	8.35142	2.58932
7	1.0	0.5	0.1	0.1	1	0.34	3.36482	1.05214
8	1.0	0.5	0.1	0.1	1	0.30	3.13925	0.83549

In order to get physical insight of the problem, calculations have been made for velocity, temperature, concentration, skin friction and Nusselt number. Effects of different parameters viz. M (magnetic parameter), k (chemical reaction parameter), h_1 (velocity slip papameter), h_2 (temperature jump parameter), S_c (Schmidt number), A (suction parameter), G_r (thermal Grasof number), G_c(mass Grashof number) and P_r (Prandtl number) are discussed and shown graphically. We fix ∈ = 0.02, n = 0.1, E_c = 0.01 and k = 5.

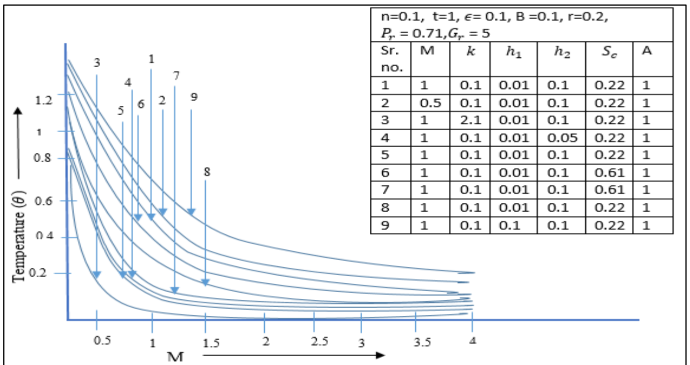
Velocity profiles are plotted against y, in figure 3.2, fixing α =1, P_r =0.71, G_r =5 and G_c =0.6. We observe that on increasing M_1,k_1,h_1, and S_c, velocity drops whereas, velocity rises on increasing A and h_2.Moreover, it is observe that for higher values of S_c on increasing its value, velocity rises near the plate but then drops as we move away. It is noteworthy that for the case of no slip (h_1 = 0), velocity drops near the plate, but then rises as we move away as compared to (h_1 ≠0).

In figure 3.3 the temperature profiles are plotted against y, fixing α =1, P_r =0.71, G_r =5 and G_e =0.6. From the figure it is observed that inscreasing values of $M_1 h_1$ and S_c increases the temperature but increase in k_1 A and h_2 decrease it. It is further investigated that temperature is more for carbon dioxide (S_c =0.94) as compared to oxygen (S_c =0.66).



∈ = 0.1, n = 0.1, t = 1, R = 0.2, P_r = 0.71, ∝ = 1,						
Sr. no.	M	k	h_1	h_2	S_c	A
1	1	10	0.5	0.1	0.25	1
2	0.5	10	0.5	0.1	0.25	1
3	1	10	0.2	0.1	0.25	1
4	1	10	0.5	0.1	0.25	1
5	1	10	0.5	0.05	0.25	1
6	1	10	0.5	0.1	0.25	1
7	1	10	0.5	0.1	1.14	1
8	1	10	0.5	0.1	0.25	1
9	1	10	0.5	0.1	0.25	1

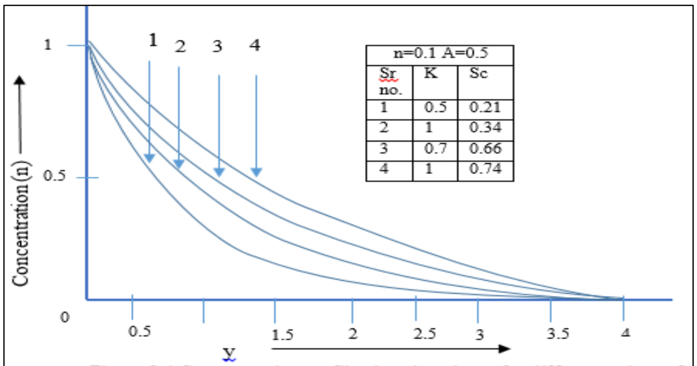
Figure 3.2 Velocity profile placed against y for different values of M, A, k, h_1, h_2 and S_c.



n=0.1, t=1, ϵ= 0.1, B =0.1, r=0.2, P_r = 0.71,G_r = 5						
Sr. no.	M	k	h_1	h_2	S_c	A
1	1	0.1	0.01	0.1	0.22	1
2	0.5	0.1	0.01	0.1	0.22	1
3	1	2.1	0.01	0.1	0.22	1
4	1	0.1	0.01	0.05	0.22	1
5	1	0.1	0.01	0.1	0.22	1
6	1	0.1	0.01	0.1	0.61	1
7	1	0.1	0.01	0.1	0.61	1
8	1	0.1	0.01	0.1	0.22	1
9	1	0.1	0.1	0.1	0.22	1

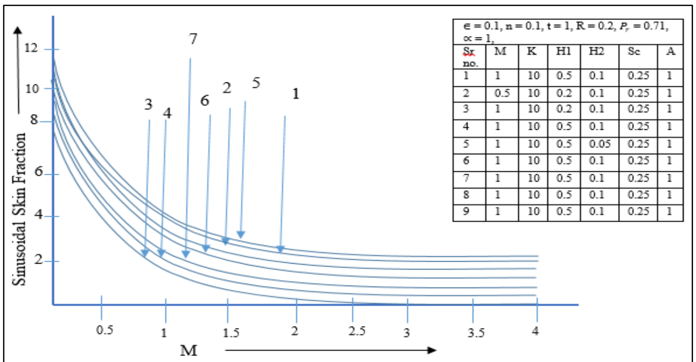
Figure 3.3 Temperature profile placed against y for different values of M, k, h_1, h_2, A and S_c.

Figure 3.4 illustrates the concentration profiles for Schmidt number (S_c) and chemical reaction parameter (k), we notice that effects of increasing values of S_c and k is to decrease the concentration. It is further observed that concentration profile is less for carbon dioxide (S_c =0.94) as compared to oxygen (S_c =0.66).An important parameter, namely sinusoidal skin friction is plotted against M in figure 3.5, fixing α =1. From the figure, we observe that on decreasing G_r, K,h_2, h_1 and P_r, skin friction rises on the other hand it drops on decreasing Ge and Sc. It is noteworthy that when h_2 =0 (no jump in temperature), skin friction increases further as compared to h_2 ≠0.



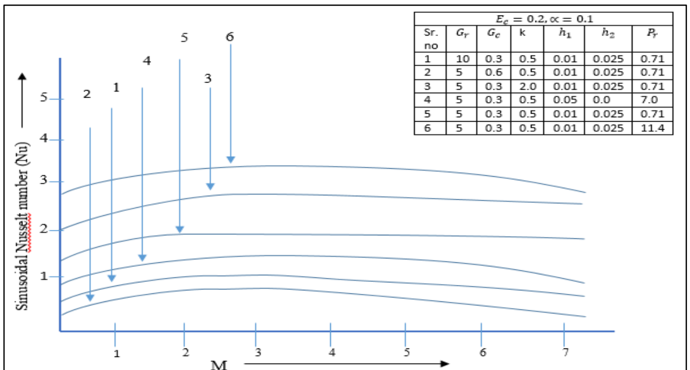
n=0.1 A=0.5		
Sr. no.	K	Sc
1	0.5	0.21
2	1	0.34
3	0.7	0.66
4	1	0.74

Figure 3.4 Concentration profile placed against y for different values of k and S_c.



∈ = 0.1, n = 0.1, t = 1, R = 0.2, P_r = 0.71, ∝ = 1,						
Sr. no.	M	K	H1	H2	Sc	A
1	1	10	0.5	0.1	0.25	1
2	0.5	10	0.2	0.1	0.25	1
3	1	10	0.2	0.1	0.25	1
4	1	10	0.5	0.1	0.25	1
5	1	10	0.5	0.05	0.25	1
6	1	10	0.5	0.1	0.25	1
7	1	10	0.5	0.1	0.25	1
8	1	10	0.5	0.1	0.25	1
9	1	10	0.5	0.1	0.25	1

Figure 3.5 Sinusoidal skin Fraction placed against M for different values of $G_r, G_c, k, h_1, h_2, P_r$ and S_c.



$E_c = 0.2, \propto = 0.1$						
Sr. no	G_r	G_c	k	h_1	h_2	P_r
1	10	0.3	0.5	0.01	0.025	0.71
2	5	0.6	0.5	0.01	0.025	0.71
3	5	0.3	2.0	0.01	0.025	0.71
4	5	0.3	0.5	0.05	0.0	7.0
5	5	0.3	0.5	0.01	0.025	0.71
6	5	0.3	0.5	0.01	0.025	11.4

Figure 3.6 Sinusoidal Nusselt number placed against M for different values of $G_r, G_c, k, h_1, h_2, P_r$ and S_c.

In figure 3.6, sinusoidal Nusselt number is plotted against M, fixing α = 1. We observe that on increasing G_r, k, h_1 andP_r, the rate of heat transfer rises where as it drops on increasing G_c and h_2, h_2= 0 (no jump in temperature), the rate of heat transfer raised further as compared to $h_2 \neq 0$. Physically increase in thermal Grashof number (G_r) and chemical reaction parameter (k) will increase the heat generation and hence more heat loss will take place as a result temperatures will drop and rate of heat transfer rises.

7. References

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