Radiation and Chemical Reaction Effects on Thermophoretic MHD Flow over an Aligned Isothermal Permeable Surface with Heat Source

C S K Raju[1] N.Sandeep[1*] M.Jayachandra Babu[1] V.Sugunamma[2]
1.Department of Mathematics, VIT University, Vellore (T.N.) - 632014, India
2.Department of Mathematics, Sri Venkateswara University, Tirupati (A.P.) -517502, India
E-mail: nsreddy.dr@gmail.com

Abstract
Radiation and chemical reaction effects on thermophoretic MHD flow over an inclined isothermal permeable surface in presence of heat generation/absorption, viscous dissipation is analyzed numerically. The governing equations are reduced to nonlinear ordinary differential equations by using similarity transformation and then solved numerically using bvp4c solver with MATLAB Package. The effects of governing parameters on dimensionless quantities like velocity, temperature, concentration, skin friction, wall heat flux and wall deposition flux are discussed for both suction and injection cases. Results are presented graphically and through tables.
Keywords: Magnetohydrodynamics, Thermophresis, Radiation, Dissipation, Heat source.

1. Introduction
Thermophoresis has potential applications like air cleaning, aerosol particles sampling, nuclear reactor safety, micro electronics manufacturing etc. Thermophoresis describes the migration of suspended small micron sized particles in a non isothermal gas to the direction with decreasing thermal gradient and the velocity acquired by the particle is known as thermophoretic velocity. The detailed discussion about this study was given by (Derjaguin and Yalamov, 1965). Thermophoresis of aerosol particles in laminar boundary layer on flat plate was analyzed by (Goren, 1977).

Thermophoretic hydromagnetic flow over radiate isothermal inclined plate by considering heat source was discussed by (Noor et.al, 2013). They used shooting method to solve the problem. (Prasad et al., 2010) considered viscoelastic fluid over a stretching sheet and analyzed the momentum and heat transfer characteristics of the boundary layers of an incompressible electrically conducting fluid. (Ramana Reddy et al. 2014, Mohan Krishna et al. 2014, Sandeep et al. 2013) are discussed the heat transfer characteristics on nanofluids by immersing the high conductivity nano materials in base fluids and they concluded that the effective thermal conductivity of the fluid increases appreciably and consequently enhances the heat transfer characteristics by suspending the high thermal conductivity of nano materials in to the base fluids. (Sandeep et al., 2012) analyzed the effect of radiation and chemical reaction on transient MHD free convective flow over a vertical plate through porous media. (Mishra et. al, 2005) have studied the two-dimensional transient conduction and radiation heat transfer with temperature dependent thermal conductivity. (Attia, 2006) studied the unsteady couette flow with heat transfer on dusty fluid with variable physical properties. Radiation and chemical reaction effects on convective flow of a dusty fluid were studied by (Mohan Krishna et al., 2013). Sugunamma and Sandeep (2011) examined unsteady hydrmagnetic free convection flow of a dissipative and radiating fluid past a vertical plate through porous media with constant heat flux. Magnetic field effects on electrically conducting free convection heat and mass transfer from an inclined plate with heat generation/absorption was studied by (Chamkha et al., 2001).

To the author’s knowledge no studies has been analyzed the Radiation and chemical reaction effects on thermophoretic MHD flow over an inclined isothermal permeable surface in presence of heat generation/absorption, viscous dissipation. The governing equations are solved numerically by using bvp4c solver with MATLAB Package. In this study we investigate the effects of governing parameters on dimensionless quantities like velocity, temperature, concentration, skin friction, wall heat flux and wall deposition flux are discussed for both suction and injection cases. And results are presented graphically and through tables.

2. Mathematical Formulation
Consider two dimensional steady laminar incompressible flow of an electrically conducting fluid over a continuously moving semi-infinite inclined permeable flat plate with an angle α .The plate is along the x -axis and y is normal to the flow. The transverse magneticfield $B(x)$ is applied along y direction. Suction/injection imposed on the permeable plate. Uniform heat source with chemical reaction and thermophoretic is taken in to account. The boundary layer equations that governs the present flow subject to the

Boussinesq approximations can be expressed as

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)\cos\alpha+g\beta^*(C-C_\infty)\cos\alpha-\frac{\sigma B^2(x)}{\rho}u-\frac{\upsilon}{k}u \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\lambda_g}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{Q(x)}{\rho c_p}(T-T_\infty)+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2-\frac{\sigma B^2(x)}{\rho c_p}u^2 \quad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 T}{\partial y^2}-V_T\frac{\partial C}{\partial y}-C\frac{\partial V_T}{\partial y}-k_1(C-C_\infty) \quad (4)$$

Where u and v are the velocity components in the x,y directions , υ is the kinematic viscosity, g is the acceleration due to gravity , β,β^* are the volumetric coefficients of thermal expansion and concentration, T, T_w *and* T_∞ are the temperatures of thermal boundary layer fluid ,the inclined plate and the free stream respectively, σ is the electrical conductivity , $B(x)=B_0/\sqrt{2x}$ is the magnetic induction , λ_g is the fluid thermal conductivity, ρ is the fluid density , c_p is the specific heat at constant pressure , q_r is the radiative heat flux in the y-direction, $Q(x)=Q_0/x$ is the internal heating , μ is the dynamic viscosity is the molecular diffusivity of the species concentration, k_1 is the chemical reaction parameter and V_T is the thermophoretic velocity. The Boundary conditions for the model as follows

$$u=U_0,\ v=\pm v_w(x),\ T=T_w,\ C=C_w \quad at \quad y=0,$$
$$u=0,\quad T=T_\infty,\quad C=C_\infty \qquad as \qquad y\to\infty, \quad (5)$$

Where U_0 is the uniform plate velocity and $v_w(x)$ represents fluid suction/injection on the porous surface .The transpiration function variable $v_w(x)$ of order $x^{-1/2}$ is considered. The radiative heat flux q_r under Rosseland approximation has the form

$$q_r=-\frac{4\sigma_1}{3\chi}\frac{\partial T^4}{\partial y} \quad (6)$$

where σ_1 is the Stefan-Boltzmann constant and χ is the mean absorption coefficient. The temperature differences within the flow are assumed to be sufficiently small such that T^4 may be expressed as a linear function of temperature. Expanding T^4 using Taylor series and neglecting higher order terms yields

$$T^4\cong 4T_\infty{}^3T-3T_\infty{}^4 \quad (7)$$

Substituting equations (6) , (7) in (3) we have

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\lambda_g}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma_1 T^3{}_\infty}{3\rho c_p\chi}\frac{\partial^2 T}{\partial y^2}+\frac{Q(x)}{\rho c_p}(T-T_\infty)+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2-\frac{\sigma B^2(x)}{\rho c_p}u^2 \quad (8)$$

The thermophoretic velocity V_T in equation (4) can be written as

$$V_T=-k\upsilon\frac{\nabla T}{T_r}=-\frac{k\upsilon}{T_r}\frac{\partial T}{\partial y} \quad (9)$$

Where T_r is a reference temperature and k is the thermophoretic coefficient which is given by

$$k=\frac{2C_s(\lambda_g/\lambda_p+C_tKn)[C_1+C_2e^{\frac{-C_3}{Kn}}]}{(1+3C_mKn)(1+2\lambda_g/\lambda_p+2C_tKn)} \quad (10)$$

Where C_1,C_2,C_3,C_m,C_s,C_t are constants λ_g,λ_p are the thermal conductivities of the fluid and diffused particles respectively and Kn is the Knudsen number .A thermophoretic parameter τ can be defined as

$$\tau = -\frac{k(T_w - T_\infty)}{T_r} \tag{11}$$

The governing equations (2)-(4) can be transformed to a set of nonlinear ordinary differential equations by introducing the following non-dimensional variables

$$\eta = y\sqrt{\frac{U_0}{2\upsilon x}}, \quad \psi = \sqrt{2U_0\upsilon x}\, f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \tag{12}$$

Where ψ is the stream function that satisfies the continuity equation (1) with

$$u = \frac{\partial \psi}{\partial y} = U_0 f'(\eta) \;\; and \;\; v = -\frac{\partial \psi}{\partial x} = \sqrt{\frac{U_0\upsilon}{2x}}\left[f(\eta) - \eta f'(\eta)\right] \tag{13}$$

Using (12) and (13) in (2) to (4) the following similarity equations with the corresponding boundary conditions are obtained

$$f''' + ff'' + \gamma\theta\cos\alpha + \gamma_1\phi\cos\alpha - (M + K_p)f' = 0 \tag{14}$$

$$(3R+4)\theta'' + 3R\Pr\left(f\theta' + Ec(f'')^2 - EcM(f')^2 + 2\delta\theta\right) = 0 \tag{15}$$

$$\phi'' + Sc(f - \tau\theta')\phi' - Sc\tau\theta''(\phi + \tau_1\phi') - K_l\phi = 0 \tag{16}$$

Subject to

$$f = f_w, f' = 1, \theta = 1, \phi = 0 \;\; at \;\; \eta = 0$$
$$f' = 0, \theta = 0, \phi = 1, \;\; as \;\; \eta \to \infty \tag{17}$$

Here $\gamma = Gr_x / \mathrm{Re}_x^{\,2}, \gamma_1 = Gc_x / \mathrm{Re}_x^{\,2}$ are the local buoyancy parameters , $Gr_x = g\beta(T_w - T_\infty)(2x)^3/\upsilon^2, Gc_x = g\beta^*(C_w - C_\infty)(2x)^3/\upsilon^2$ are the thermal and mass Grashof numbers respectively , $\mathrm{Re}_x = 2xU_0/\upsilon$ is the local Reynolds number , $M = \sigma B_0^{\,2}/\rho u_0$ is the Hartmann number , $R = \lambda_g\chi/4\sigma_1 T_\infty^{\,3}$ is the Radiation parameter, $\Pr = \upsilon\rho c_p/\lambda_g$ is the Prandtl number , $Ec = U_0^{\,2}/c_p(T_w - T_\infty)$ is the Eckert number , $\delta = Q_0/\rho c_p U_0$ is the internal heat source /sink, $Sc = \upsilon/D$ is the Schmidt number and $f_w = -v_w(x)\sqrt{2x/U_0\upsilon}$ is the permeability of the porous surface with positive value indicates suction while negative value indicates injection. $k_l = \mathrm{Re}_x k_1\upsilon/U_0^2$ is the chemical reaction parameter and $\tau_1 = C_\infty/(C_w - C_\infty)$ is the ratio of ambient concentration to the difference between the concentrations near the wall and ambient.

The physical quantities of interest are the local skin friction coefficient, the wall heat transfer coefficient (or the local Nusselt number) and the wall deposition flux (or the local Stanton number) which are defined as

$$Cf_x = \frac{\tau_w}{\rho U_0^{\,2}/2}, \quad Nu_x = \frac{q_w x}{\lambda_g(T_w - T_\infty)}, \quad St_x = -\frac{J_s}{U_0 C_\infty}, \tag{18}$$

Respectively where the skin friction τ_w, the heat transfer from the wall q_w and the deposition flux from wall J_s are given by

$$\tau_w = \mu\left(\frac{\partial c}{\partial y}\right)_{y=0}, q_w = -\lambda_g\left(\frac{\partial c}{\partial y}\right)_{y=0} - \frac{4\sigma_1}{3\chi}\left(\frac{\partial T^4}{\partial y}\right)_{y=0}, J_s = -D\left(\frac{\partial c}{\partial y}\right)_{y=0} \tag{19}$$

Hence the expressions for the skin friction, the rate of heat transfer and the deposition flux for general flow over a radiative surface are written as

$$Cf_x \mathrm{Re}_x^{\,1/2} = 2f''(0), \;\; Nu_x \mathrm{Re}_x^{\,-1/2}\left(\frac{3R}{3R+4}\right) = -\frac{1}{2}\theta'(0), \;\; St_x Sc\,\mathrm{Re}_x^{\,1/2} = \phi'(0) \tag{20}$$

3. Numerical solution

Equations (14) to (16) with the boundary conditions (17) have been solved numerically using bvp4c solver with

MATLAB Package. Equations (14) to (16) are transformed into systems of first order differential equations. We can check the accuracy of the assumed missing initial condition, by comparing the calculated value of the different variables at the terminal point with the given value by the existence of the difference in improved values the missing initial conditions must be obtained. The calculations are carried out by the program using MATLAB package.

4. Results and discussion

The results obtained shows the influences of the non dimensional governing parameters, namely Magneticfield parameter M, Heat generation/absorption parameter δ, Thermophoretic parameter τ, Porosity parameter K_p, Chemical reaction parameter K_l and Radiation parameter R on the velocity profile, temperature profile, concentration profile, friction factor, local Nusselt and the deposition flux. For numerical results we considered $\alpha = \pi/6, Ec = 0.1, Sc = 0.6, \tau = 1, \tau_1 = 1, t = 1$

$\gamma = 4, \gamma_1 = 4, K_p = 0.1, K_l = 0.1, \Pr = 0.7, R = 1, \mathrm{M} = 1$ except for varied values shown in figures.

Figures 1, 2 and 3 shows the effect of magneticfield parameter on velocity, temperature and concentration profiles respectively. From figure 1 it is clear that increase in magneticfield parameter causes the decrease in velocity profiles of the fluid. It is due to the fact that there exists an opposite force to the flow called Lorentz force and it is evident that the effect of magnetic field is high in suction case compared to injection case. Similar type of result observed in the temperature profiles of the fluid which depicts in figure 2. But from figure 3 it is interesting to note that the increase in magnetic field decreases the concentration profiles of the fluid and this influence is more on injection case but it is opposite to velocity and temperature profiles where magneticfield effect is more on suction case. It may happen due to the fact that injection causes the increase in concentration of the fluid.

Figures 4, 5 and 6 illustrates the influence of heat source parameter on velocity, temperature and concentration profiles respectively. From figures 4 and 5 it is observed that increase in heat source parameter increases the velocity and temperature profiles of the fluid. It is evident from figures that heat source effect is more in injection case compared to suction case. The reason behind this is increase in heat source enhances the fluid temperature and it helps to reduce the boundary layer thickness. Figures 7, 8 and 9 depict the effect of thermophoretic parameter on velocity, temperature and concentration profiles respectively. It is clear that increase in thermophoretic parameter increases the velocity and concentration profiles of the fluid as shown in figures 7 and 9.But this parameter does not shown significant difference in temperature profiles of the fluid as observed in figure 8.These may be happened due to the unique appearance of thermophoretic parameter in diffusion equation and there is cross relation between velocity and diffusion but no relation with temperature. Figures 10, 11 and 12 shows the effect of chemical reaction parameter on velocity, temperature and concentration profiles respectively.

From figures 10 and 12 it is observed that increase in chemical reaction parameter enhances the velocity as well as concentration profiles of the fluid and we seen the mixed performance in suction and injection cases. But chemical reaction parameter has tendency to reduce the temperature profiles of the fluid as shown in figure 11. Figures13, 14 and 15 shows the effect of porosity parameter on velocity, temperature and concentration profiles respectively. It is evident from figures 13 and 15 that increase in porosity parameter reduces the velocity and concentration profiles of the fluid for both suction and injection cases but it helps to enhance the temperature profiles of the fluid as shown in figure14. The reason behind this is increase in porosity generates the internal heat.

Figures 16, 17 and 18 shows the effect of radiation parameter on velocity, temperature and concentration profiles respectively. It is clear from figures 16 and 18 that increase in radiation parameter decreases the velocity and concentration profiles of the fluid. The reason for decreasing the fluid velocity is due to the domination of absorptive coefficient in radiation parameter. From figures 17 it is evident that increase in radiation decreases the temperature of the fluid up to certain period afterwards it takes reverse action and helps to enhance the temperature of the flow. Figures 19 and 20 display the effect of acute angle on velocity and temperature profiles respectively. It is evident that increase in acute angle increases the velocity as well as temperature profiles of the fluid for both suction and injection cases at $\eta = 1.4\ to 1.6$ temperature profiles takes reverse action as shown in figure 20.

Table-1 shows the effect of physical parameters on friction factor, local Nusselt and the deposition flux. It is clear from the table that increase in acute angle reduces the friction coefficient as well as deposition flux but it improves the heat transfer rate in both suction and injection cases. Increase in heat source parameter increases the skin friction coefficient and decreases the heat transfer rate and deposition flux in both cases. Increase in chemical reaction parameter decreases the friction coefficient as well as deposition flux but it enhances the heat transfer rate in both suction and injection cases. Increase in radiation parameter increases friction coefficient but decreases heat transfer rate and deposition flux in both cases. Viscous dissipation parameter follows the radiation parameter. Increase in porosity parameter decreases the friction coefficient and deposition flux but increases the heat transfer rate in both suction and injection cases.

Table 1: Values of $f''(0), -\theta'(0)$ *and* $\phi'(0)$ for $\gamma = \gamma_1 = 10, \Pr = 0.7, Sc = 0.2, \tau = 1$

f_w	α	δ	k_l	R	Ec	k_p	$f''(0)$	$-\theta'(0)$	$\phi'(0)$
0.5	$\pi/6$	1	1	1	0.1	0.2	5.347379	0.348593	0.414724
	$\pi/4$	1	1	1	0.1	0.2	4.199863	0.364578	0.406024
	$\pi/3$	1	1	1	0.1	0.2	2.665195	0.371159	0.392780
-0.5	$\pi/6$	1	1	1	0.1	0.2	4.678905	0.249622	0.348456
	$\pi/4$	1	1	1	0.1	0.2	3.711067	0.265237	0.340198
	$\pi/3$	1	1	1	0.1	0.2	2.429686	0.272509	0.327924
0.5	$\pi/6$	**0**	1	1	0.1	0.2	4.979521	0.610509	0.426376
	$\pi/6$	**1**	1	1	0.1	0.2	5.347379	0.348593	0.414724
	$\pi/6$	**2**	1	1	0.1	0.2	5.833607	0.019964	0.400901
-0.5	$\pi/6$	**0**	1	1	0.1	0.2	4.359868	0.513105	0.358063
	$\pi/6$	**1**	1	1	0.1	0.2	4.678905	0.249622	0.348456
	$\pi/6$	**2**	1	1	0.1	0.2	5.101256	-0.081837	0.337003
0.5	$\pi/6$	1	**0**	1	0.1	0.2	6.137460	0.328001	0.733702
	$\pi/6$	1	**1**	1	0.1	0.2	5.347379	0.348593	0.414724
	$\pi/6$	1	**2**	1	0.1	0.2	4.903958	0.356540	0.254839
-0.5	$\pi/6$	1	**0**	1	0.1	0.2	5.252935	0.231376	0.619184
	$\pi/6$	1	**1**	1	0.1	0.2	4.678905	0.249622	0.348456
	$\pi/6$	1	**2**	1	0.1	0.2	4.363177	0.256879	0.213698
0.5	$\pi/6$	1	1	**0.1**	0.1	0.2	5.294645	0.349783	0.383985
	$\pi/6$	1	1	**0.5**	0.1	0.2	5.318138	0.349259	0.397469
	$\pi/6$	1	1	**1**	0.1	0.2	5.347379	0.348593	0.414724
-0.5	$\pi/6$	1	1	**0.1**	0.1	0.2	4.630490	0.250926	0.319720
	$\pi/6$	1	1	**0.5**	0.1	0.2	4.651935	0.250354	0.332287
	$\pi/6$	1	1	**1**	0.1	0.2	4.678905	0.249622	0.348456
0.5	$\pi/6$	1	1	1	**0.5**	0.2	5.639544	-0.035201	0.391484
	$\pi/6$	1	1	1	**1**	0.2	6.158917	-0.727130	0.352293
	$\pi/6$	1	1	1	**1.5**	0.2	7.095594	-2.006540	0.288299
-0.5	$\pi/6$	1	1	1	**0.5**	0.2	4.958367	-0.136010	0.329729
	$\pi/6$	1	1	1	**1**	0.2	5.506292	-0.891111	0.295458
	$\pi/6$	1	1	1	**1.5**	0.2	6.868639	-2.805967	0.220867
0.5	$\pi/6$	1	1	1	0.1	**0**	5.629308	0.342073	0.416635
	$\pi/6$	1	1	1	0.1	**1**	4.340307	0.366142	0.407333
	$\pi/6$	1	1	1	0.1	**2**	3.311730	0.374894	0.398957
-0.5	$\pi/6$	1	1	1	0.1	**0**	4.929033	0.242882	0.350529
	$\pi/6$	1	1	1	0.1	**1**	3.794946	0.267198	0.340608
	$\pi/6$	1	1	1	0.1	**2**	2.906307	0.275234	0.332032

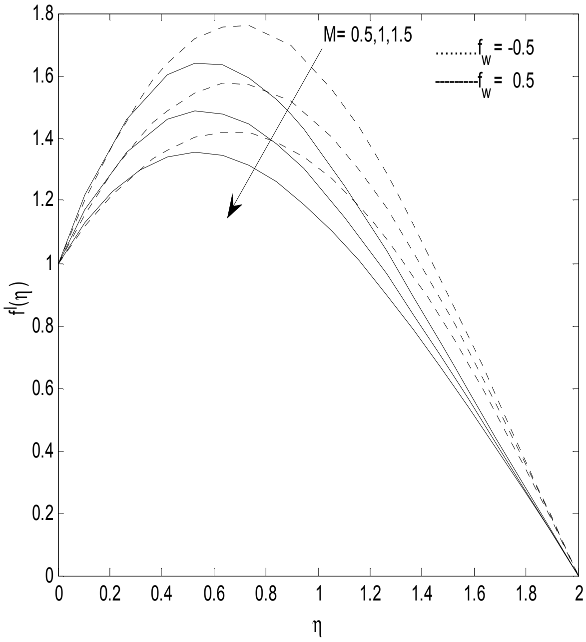

Fig..1. Velocity profiles for different values of M

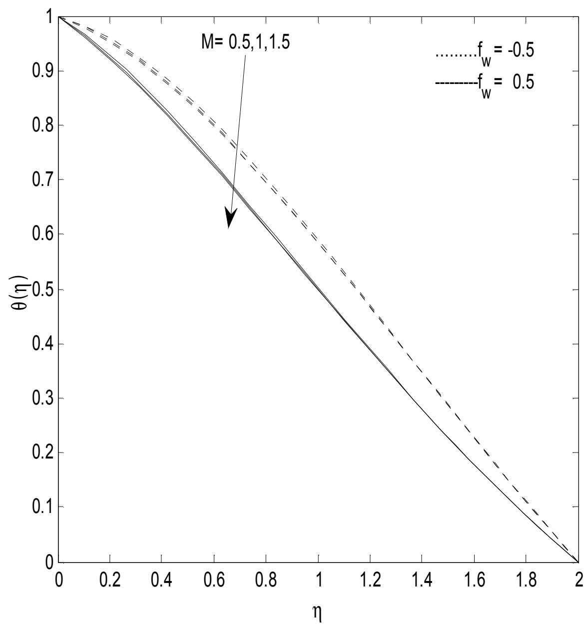

Figure. 2. Temperature profiles for different values of M

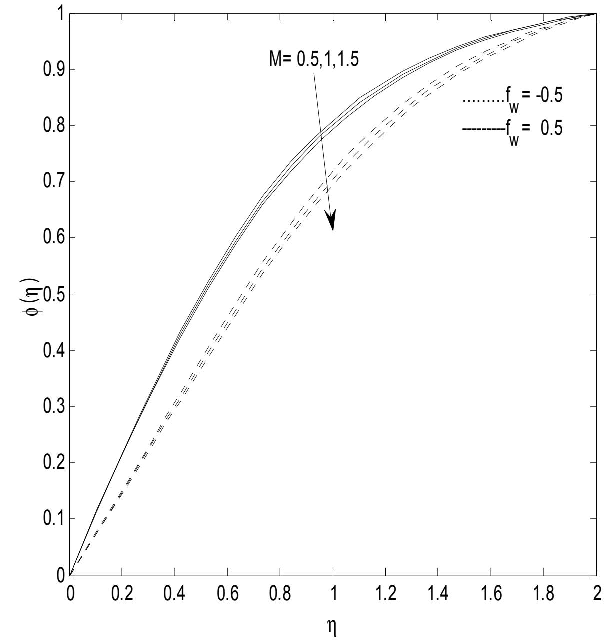

Figure.3. Concentration profiles for different values of M

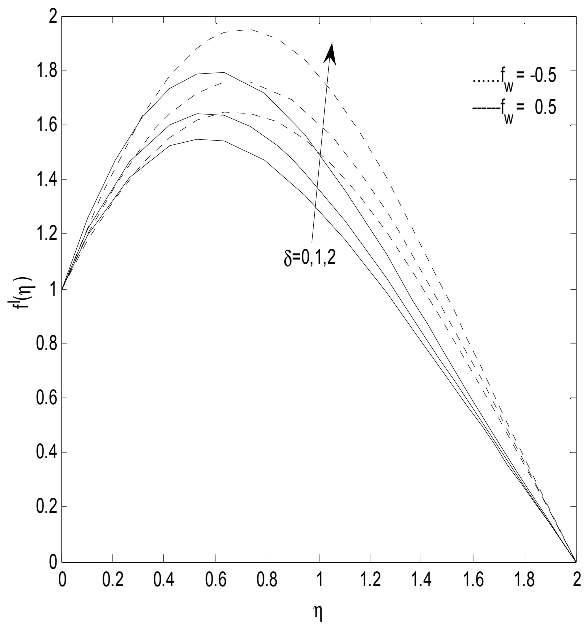

Figure. 4. Velocity profiles for different values of δ

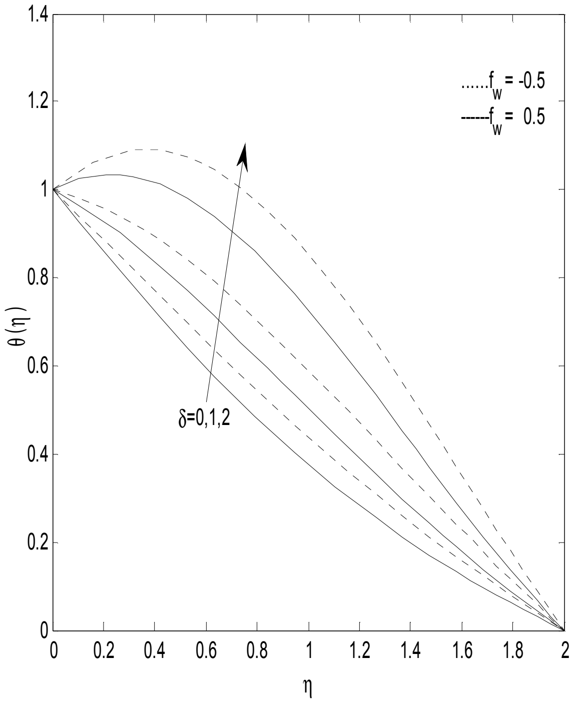

Figure.5. Temperature profiles for different values of δ

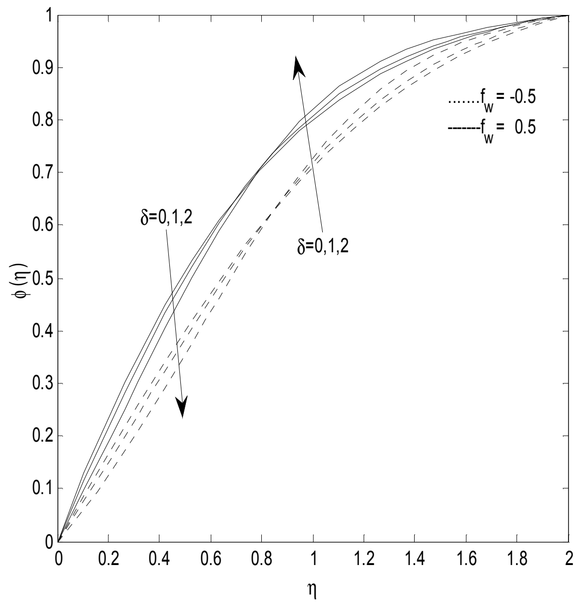

Figure.6. Concentration profiles for different values of δ

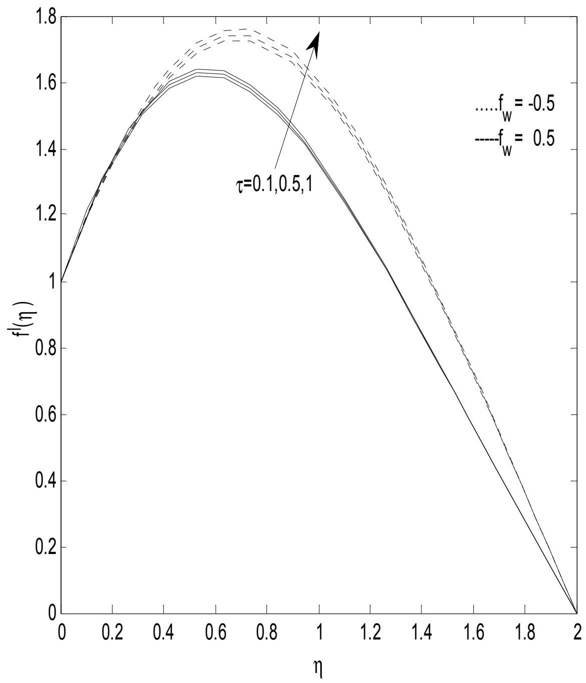

Figure. 7. Velocity profiles for different values of τ

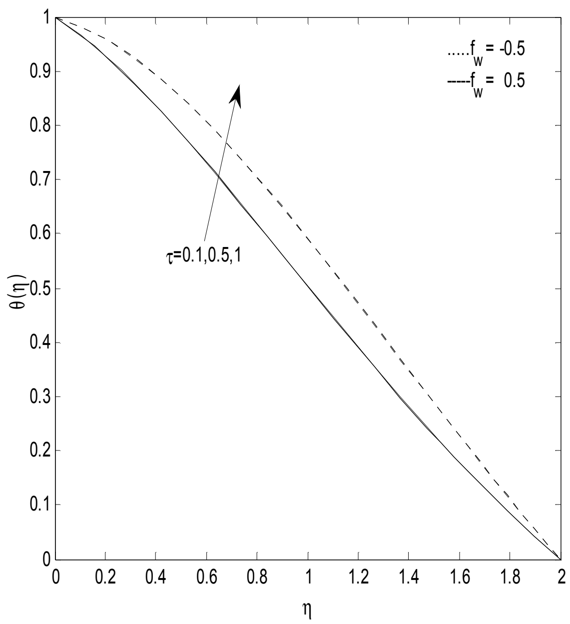

Figure. 8. Temperature profiles for different values of τ

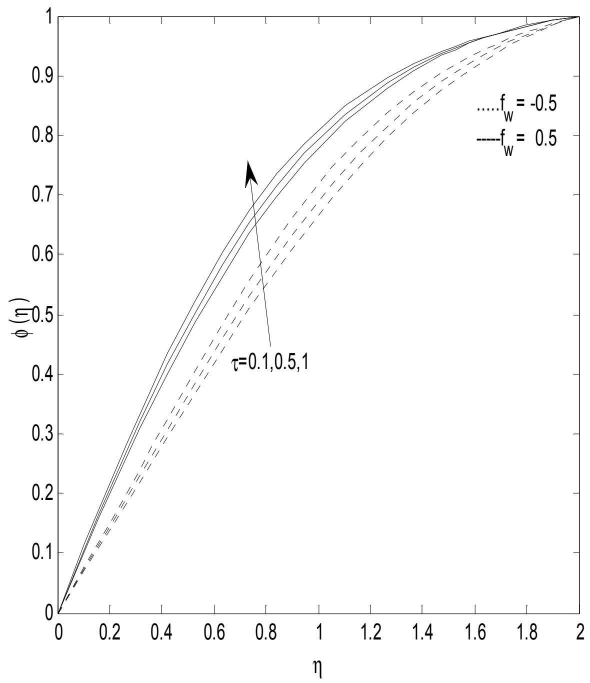

Figure. 9. Concentration profiles for different values of τ

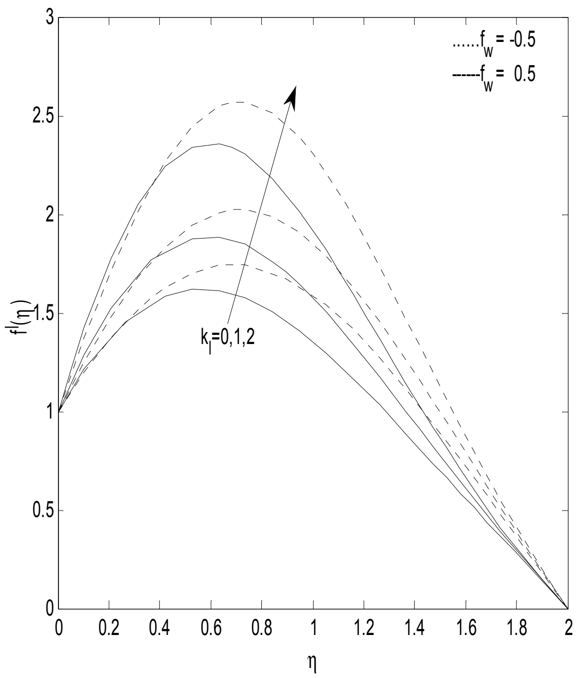

Figure. 10. Velocity profiles for different values of k_l

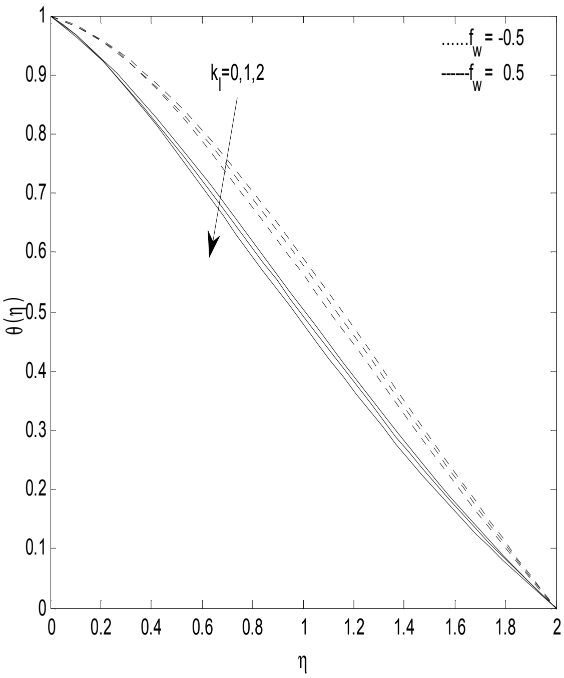

Figure.11. Temperature profiles for different values of k_l

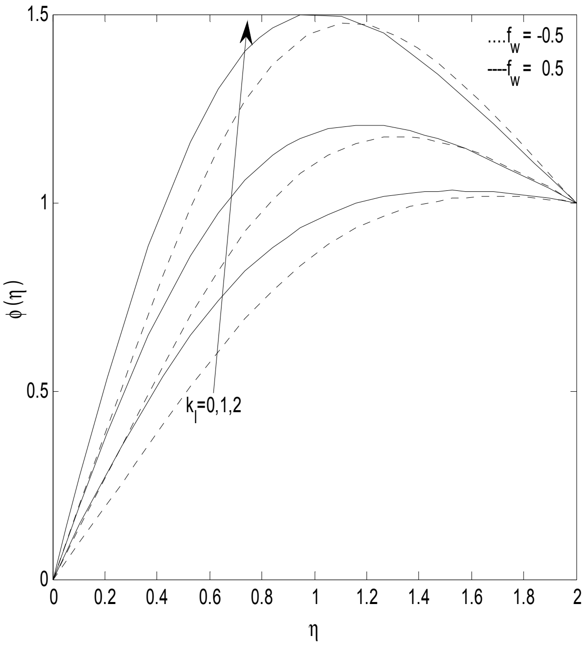

Figure.12 Concentration profiles for different values of k_l

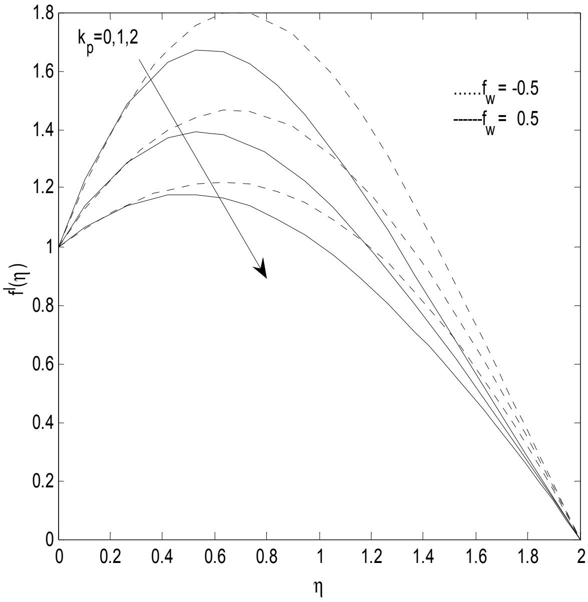

Figure.13. Velocity profiles for different values of k_p

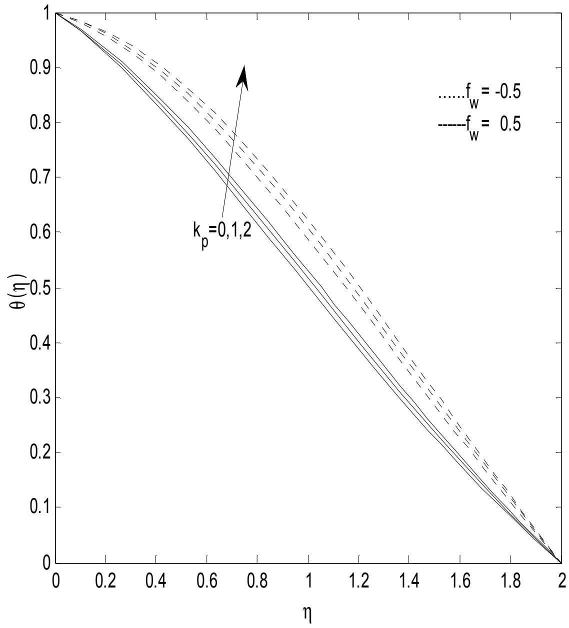

Figure.14 Temperature profiles for different values of k_p

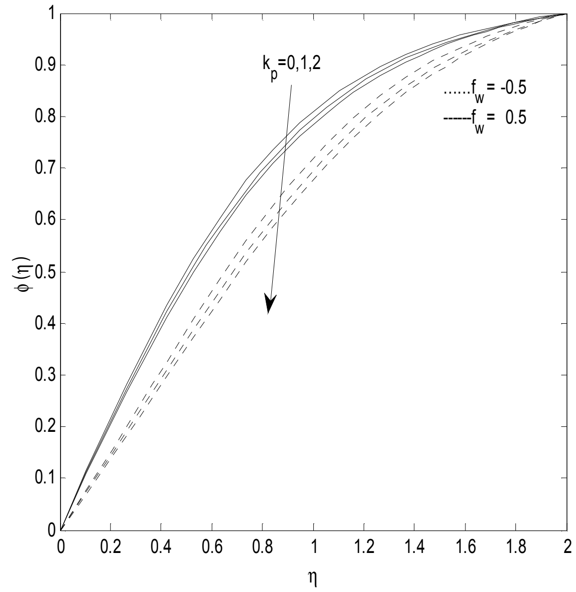

Figure.15. Concentration profiles for different values of k_p

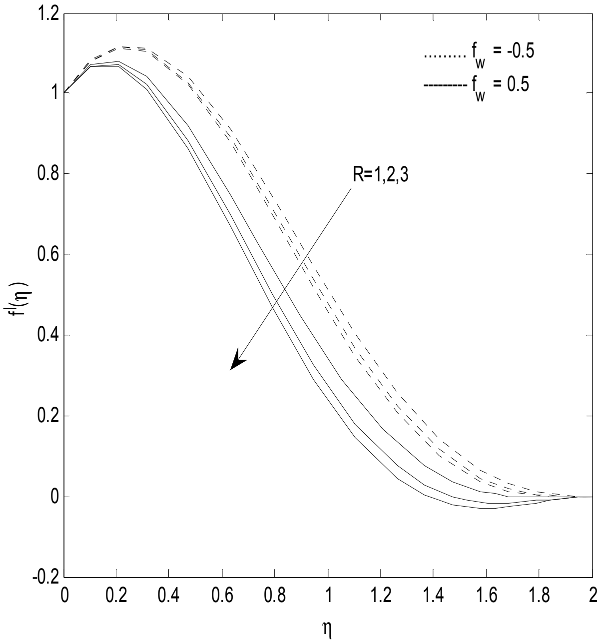

Figure.16. Velocity profiles for different values of R

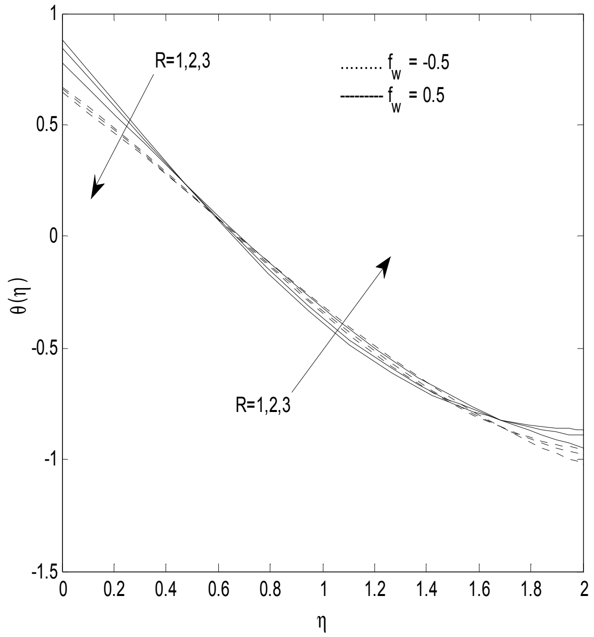

Figure.17. Temperature profiles for different values of R

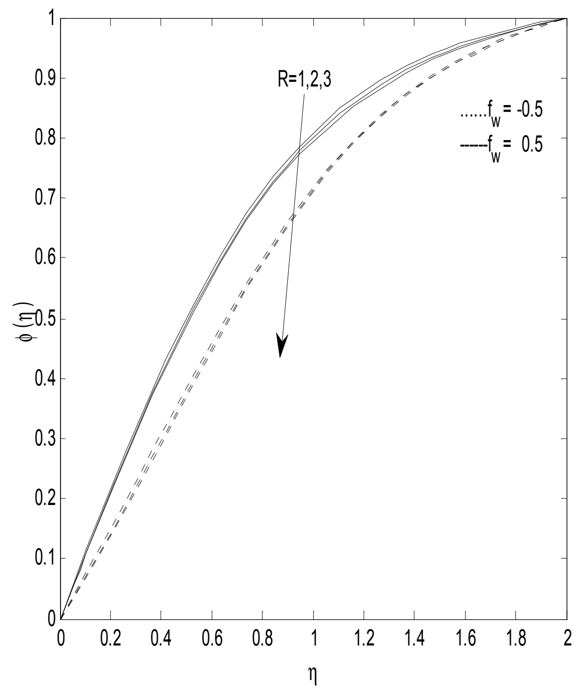

Figure.18. Concentration profiles for different values of R

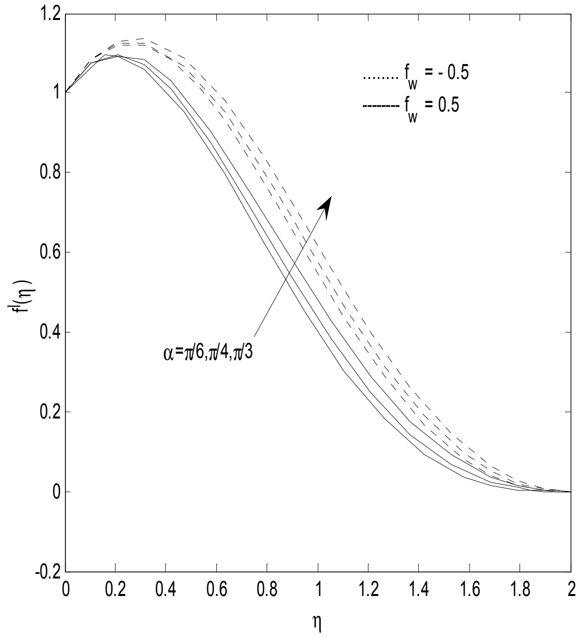

Figure.19. Velocity profiles for different values of α

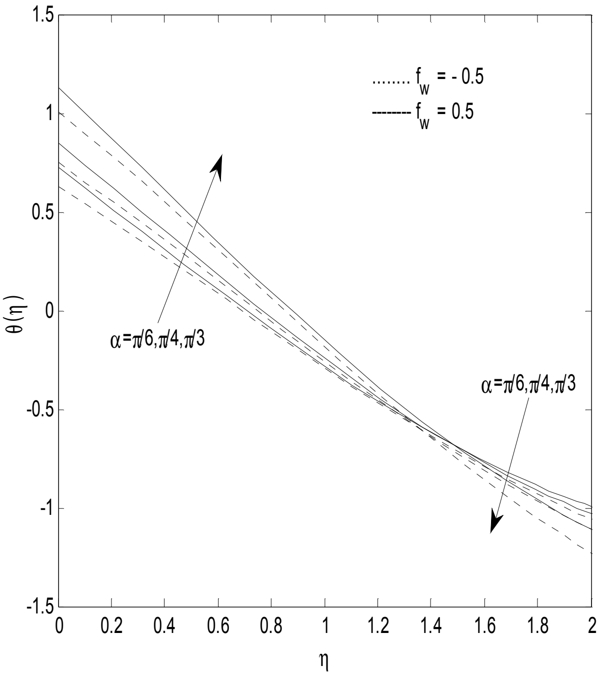

Figure.20. Temperature profiles for different values of α

5. Conclusions

This paper presents a similarity solution for the thermal radiation influenced thermophoretic MHD flow over an inclined isothermal permeable surface in presence of heat generation/absorption with viscous dissipation. By means of similarity transformation, the governing mathematical equations are reduced into ordinary differential equations which are then solved numerically bvp4c solver with MATLAB Package. The effects of some governing parameters, radiation parameter, magneticfield parameter, viscous dissipation parameter, thermophoresis parameter, acute angle, heat source parameter, porosity parameter and chemical reaction parameter on the flow, concentration and heat transfer characteristics are graphically represented and discussed. The findings of the numerical results are summarized as follows

1) The velocity profiles of is more effected by magneticfield parameter in permeable surface.
2) Heat source parameter helps to enhance the velocity, temperature and concentration profiles.
3) Radiation parameter improves the temperature profiles and decreases the concentration profiles of the fluid.
4) Velocity, temperature and concentration profiles of the flow are more influenced by suction/injection parameter.
5) Friction factor, local Nusselt and the deposition flux are more influenced by the physical parameters involved in present problem.

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