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THE COMBINED EFFECT OF CHEMICAL REACTION, HEAT AND MASS TRANSFER ON AN UNSTEADY MHD FREE CONVECTIVE FLOW EMBEDDED IN A POROUS MEDIUM WITH HEAT GENERATION/ABSORPTION

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ABSTRACT

An unsteady MHD mixed free convection two dimensional laminar, boundary layer flow of a viscous incompressible electrically conducting fluid along a semi infinite vertical porous flat plate in presence of thermal and chemical effects under the influence of uniform magnetic field applied normal to the flow has been obtained. The dimensionless governing equations are solved by using multi-parameter perturbation technique. The results are obtained for mean velocity, mean temperature, mean concentration, nusselt number of mean temperature and skin friction of mean velocity. The effect of various material parameters are discussed for cooling (Gr>0) and heating (Gr<0) of the plate on flow variables and presented by graphs and tables.

Keyword: *MHD flow, free convection, mass transfer, heat transfer, chemical reaction, porous medium, buoyancy effect.*

NOMENCLATURE

g	acceleration due to gravity
K^*	chemical reaction rate constant
T'	temperature of the fluid
T_1'	temperature near the plate
T_∞'	temperature far away from the plate
Gr	Grashoff number for heat transfer
Gm	Grashoff number of mass transfer
Pr	Prandtl number
Nu	Nusselt number
Re	Reynolds's number
Sh	Sherwood number
C'	concentration of the fluid
C_1'	concentration near the plate
C_∞'	concentration far away from the plate
C_P	specific heat at constant pressure
M	Hartmann number
Sc	Schmidt number
K	chemical reaction parameter
S	sink strength
D	chemical molecular diffusivity
B_0	the electromagnetic induction

H_0	strength of magnetic field
Nr	Radiation parameter
u	axial velocity
κ	thermal conductivity
v_0	constant suction velocity
q_r	radiative heat flux

Greek Symbols

ω	frequency of oscillations
σ	electrical conductivity
σ^*	Stefan Boltzmann constant
β	the co-efficient of thermal expansion
v	the kinematic viscosity
β_c	the coefficient of expansion of mass
ρ	density
η	axial variable
t	time variable
θ	non dimensional temperature
φ	non dimensional concentration
μ_e	magnetic permeability
ε	the small positive number

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1. INTRODUCTION

The problems on fluid flow and mass transfer through porous medium in rotating environment have significant role in the application of geophysics, petrochemical engineering, meteorology, oceanography and aeronautics. The stimulus for scientific research on rotating fluid system is basically originated from geophysical and fluid engineering applications. Many aspects of the motion of terrestrial and planetary atmospheres are highly influenced by the effect of rotation. Rotation flow theory is utilized in determining the viscosity of the fluid, in the construction of the turbine and other centrifugal machines.

The study of effects of magnetic field on free convection flow is important in liquid metals, electrolytes, and ionized gases. The thermal physics of hydro-magnetic flow problems with mass transfer is of interest in power engineering and metallurgy. Free convection flows are of great interest in a number of industrial applications such as fiber and granular insulation, geothermal systems etc. Hydro-magnetic oscillatory flows of viscous fluids over and through a porous medium has been the subject of intensive studies in recent years because of its applications in branches of engineering and sciences, viz. in the field of agricultural engineering to study the underground water resources, seepage of water in channels, ducts and in river beds, in chemical engineering for filtration and purification process, also in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. MHD channel flows are studied since long because of their applications in MHD generator, MHD pump, MHD flow meter etc. The study of natural convection in a vertical parallel plate channel is an important subject due to increasing practical applications in industries. Several practical systems such as electronic equipment, furnace and heat exchangers are the examples where this type of configuration exists. In last five years many investigations dealing with heat flow and mass transfer over a vertical porous plate with variable suction, heat absorption/generation or hall have been current reported. Singh[1] studied MHD free convection and mass transfer flows with Hall current, viscous dissipation, joule heating and thermal diffusion. Azzam [2] presented radiation effects on the MHD mixed free-fixed convective flow past a semi-infinite moving vertical plate for high temperature differences. Chamkha[3] presented thermal radiation and buoyancy effects on hydro-magnetic flow over an accelerating permeable surface with heat source or sink. Chen [4] studied heat and mass transfer with variable wall temperature and concentration. Hayat and Abdas [5] presented the radiation effects on MHD flow in a porous space. Ogulu and Mbeledogu [6] studied heat and mass transfer of an unsteady MHD natural convection flow of a rotating fluid past a vertical porous plat plate in presence of radiative heat transfer. Recently, Prakash *et al* [7] have studied MHD free convection and mass transfer flow of a micro-polar thermally radiating and reacting fluid with time dependent suction. Sunitha *et al.* [8] presented radiation and mass transfer effects on MHD free convection flow past an impulsively started isothermal vertical plate with dissipation. Seddeek *et al.* [9] investigated effects of radiation and variable viscosity on MHD free convective flow and mass transfer over a stretching sheet with chemical reaction. Tushar *et al.* [10] have studied the combined effects of unsteady heat, mass transfer and radiative convection flow with chemical reaction. Our present work concentrates the unsteady effect of MHD free convection flow of heat, mass transfer and chemical reaction in presence of heat generation/absorption, which is an extension work of Senapati *et.al* [11], where they obtained Effects of Chemical reaction of heat and mass transfer on an MHD free convection flow past an infinite vertical plate with constant suction. The effects of the parameters involved on the flow are discussed. The skin frictions at the wall, rate of heat transfer and the rate of mass transfer are also considered.

2. FORMULATION OF THE PROBLEM

An unsteady two dimensional free convective flow of an electrically conducting and incompressible fluid past an semi infinite vertical porous with heat generation in the presence of chemical reaction has been considered. Time dependent suction is considered normal to the flow. X'-axis is taken along the vertical plate in upward direction and the Y'-axis is taken normal to the plate in the direction of applied uniform magnetic field of strength Ho. The magnetic permeability μ_e is constant throughout the field. There exist free convection current in the vicinity of the plate. It is assumed that a fluid has constant properties and the variation of density with temperature and mass concentration are considered only in the body force term. All the variables in this flow are the function of y' and time t' only as the plate is infinite length. Initially, the temperature and mass concentration at the plate before chemical reaction are respectively T_1' and C_1', also the temperature and mass concentration of fluid are respectively T_∞' and C_∞'. Then by usual Boussinesq's approximation the unsteady flow is governed by the following equations:

Continuity equation:

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T_\infty') + g\beta_c(C' - C_\infty') - \frac{\sigma B_0^2 u'}{\rho} - \frac{v}{k'}u' \tag{2}$$

Energy equation:

$$\rho C_P\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} - \theta_0(T' - T_\infty') \tag{3}$$

Concentration equation:

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - K^*(C' - C'_\infty) \tag{4}$$

The initial and boundary conditions of the problem are

$$\left.\begin{aligned} &u' = V_0, T' = T'_1 + \epsilon(T'_1 - T'_\infty)e^{n't'}, \\ &C' = C'_1 + \epsilon(C'_1 - C'_\infty)e^{n't'} \quad \text{at} \quad y' = 0 \\ &u' = 0, T' \to T'_\infty, C' \to C'_\infty \; \text{as} \quad y' \to \infty \end{aligned}\right\} \tag{5}$$

The radiation flux on the basis of the Rosseland diffusion model for radiation heat transfer is expressed as:

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T'^4}{\partial y'} \tag{6}$$

in which σ^* and k^* are Stefan-Boltzmann constant and the spectral mean absorption coefficient of the medium. It is assumed that the temperature differences within the flow are sufficiently small such that T'^4 may be expressed as linear function of the temperature. It can be established by expanding T'^4 in a Taylor series about T'_∞ and neglecting higher order term, that T'^4 can be expressed in the following way:

$$T'^4 \approx 4T'^3_\infty T' - 3T'^4_\infty \tag{7}$$

Since the plate is assumed to be porous and through it suction with uniform velocity occurs, Equation (1) integrates to $v' = V_0$is the constant suction velocity

On introducing the following non-dimensional quantities

$$\left.\begin{aligned} &u = \frac{u'}{V_0}, y = \frac{V_0 y'}{v}, t = \frac{t'V_0^2}{v}, \theta = \frac{T' - T'_\infty}{T'_1 - T'_\infty}, \emptyset = \frac{C' - C'_\infty}{C'_1 - C'_\infty}, Pr = \frac{v\rho C_p}{k}, M = \frac{\sigma v B_0^2}{\rho V_0^2} \\ &N_r = \frac{16\sigma^* T'^3_\infty}{3k^* k}, S = \frac{v\theta_0}{\rho c_p V_0^2}, K^* = \frac{KV_0^2}{v}, Gr = \frac{g\beta v(T'_1 - T'_\infty)}{V_0^3}, Gm = \frac{g\beta_C v(C'_1 - C'_\infty)}{V_0^3}, \\ &v = \frac{v'}{V_0}, K = \frac{k'V_0^2}{v^2}, Sc = \frac{v}{D} \end{aligned}\right\} \tag{8}$$

On substitution of eq. (8) into (2),(3),(4), the following governing equations are obtained in non-dimensional form

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gm\emptyset - (M + \frac{1}{k})u \tag{9}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial \theta}{\partial y} = \left(\frac{1 + N_r}{P_r}\right)\frac{\partial^2 \theta}{\partial y^2} - S\theta \tag{10}$$

$$\frac{\partial \emptyset}{\partial t} + \frac{\partial \emptyset}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \emptyset}{\partial y^2} - k\emptyset \tag{11}$$

The corresponding initial and boundary conditions are:

$$\left.\begin{aligned} &u = 1, \theta = 1 + \varepsilon e^{nt}, \varphi = 1 + \varepsilon e^{nt} \quad \text{at y = 0} \\ &u \to 0, \theta \to 0, \varphi \to 0 \quad as\; y \to \infty \end{aligned}\right\} \tag{12}$$

The mathematical formulation of the problems is now completed. Eqs (9)-(11) are coupled non-linear systems of partial differential equations, and are to be solved by using the initial and boundary condition given in Eq. (12). However, exact solutions are difficult if possible. Hence these equations are solved by multi-parameter perturbation technique.

3. METHOD OF SOLUTION

In view of boundary condition (12), we assume the solutions of equation (9) to(11) as

$$u(y,t) = u_0(y)e^{i\omega t} \tag{13}$$

$$\theta(y,t) = \theta_0(y)e^{i\omega t} \tag{14}$$

$$\emptyset(y,t) = \emptyset_0(y)e^{i\omega t} \tag{15}$$

The boundary conditions (12) changes to

$$\left.\begin{aligned} &u_0 = e^{-i\omega t}, \theta_0 = (1 + \varepsilon e^{nt})e^{-i\omega t}, \emptyset_0 = (1 + \varepsilon e^{nt})e^{-i\omega t} \quad \text{at y=0} \\ &u_0 \to 0, \theta_0 \to 0, \emptyset_0 \to 0 \quad as\; y \to \infty \end{aligned}\right\} \tag{16}$$

Using Eqs (13),(14),(15) &(16), the solution of the Eqs (9),(10)&(11) are expressed as velocity, temperature and concentration as follows:

$$u(y) = e^{\frac{[1-\sqrt{1+4a_1}]y}{2}} - \left[(e^{\frac{[1-\sqrt{1+4a_1}]y}{2}} - 1).(A_1 e^{\frac{(P_r - \sqrt{a_2})y}{2(1+N_r)}} + A_2 e^{\frac{(Sc - \sqrt{a_3})y}{2}})\right] \tag{17}$$

$$\theta(y) = b_1 e^{\frac{(P_r - \sqrt{a_2})y}{2(1+N_r)}} \tag{18}$$

$$\emptyset(y) = b_1 e^{\frac{(Sc - \sqrt{a_3})y}{2}} \tag{19}$$

Where

$$a_1 = M + \frac{1}{K} + i\omega \,, a_2 = P_r^2 + 4(S + i\omega)(1 + N_r)P_r,$$

$$a_3 = Sc^2 + 4(i\omega + K)Sc \,, A_1 = \frac{Grb_1}{a_1}$$

$$A_2 = \frac{Gmb_1}{a_1} \,, b_1 = 1 + \varepsilon e^{nt}$$

Skin friction:

$$\tau = u^{'}(y)]_{y=0} = \frac{[1-\sqrt{1+4a_1}]}{2}[1 - A_1 - A_2] + A_1\left[\frac{(P_r-\sqrt{a_2})}{2(1+N_r)}\right] + A_2[\frac{(Sc-\sqrt{a_3})}{2}] \tag{20}$$

Nusselt number:

$$Nu = \theta^{'}(y)]_{y=0} = b_1[\frac{(P_r-\sqrt{a_2})}{2(1+N_r)}] \tag{21}$$

Sherwood number:

$$Sh = \emptyset^{'}(y)]_{y=0} = b_1[\frac{(Sc-\sqrt{a_3})}{2}] \tag{22}$$

4. RESULTS AND DISCUSSION

It is very difficult to study the influence of all governing parameters involved in the present problem ''The combined effect of chemical reaction, heat and mass transfer on an unsteady MHD free convective flow embedded in a porous medium with heat generation/absorption'. The effect of parameters Gr, Gm, Pr, Sc, M, K, Nr, S, ω on flow characteristics have been studied and shown by means of graphs and tables. Some numerical calculations are carried out for the non-dimensional velocity (u), temperature (θ),concentration (φ),skin friction coefficient /shearing stress (τ) and heat and mass transfer coefficient in terms of Nusselt number (Nu) and Sherwood number (Sh) respectively. The values of Prandtl number are chosen for air (Pr=0.72), electrolytic solution (Pr=1.0), water (Pr=5.0), water at 4^0C (Pr=9.0).The values of Schmidt number are chosen for hydrogen (Sc=0.23), water-vapour (Sc=0.60),carbon monoxide (Sc=0.76),carbon dioxide (Sc=1.0).

Velocity Profiles: The velocity profiles are depicted in Figs 1-16.

Figs 1-8 shows the effects of various parameters such as Pr, Sc, S, Nr, K, M, ω, Gr and Gm, when the plate is cooled by free-convection currents (Gr > 0). It is noticed that the velocity decreases with increase of Prandtl number(Pr), Schmidt number(Sc), Sink strength (S), Hartmann number (M), whereas increases with the increase of Chemical reaction parameter (K), Radiation parameter (Nr), Grashoff number (Gr), modified Grashoff number (Gm).From Figs 4 and 5,it is also noticed that decreases with the increase of Oscillating frequency(ω). A comparison of velocity profile curves due to cooling of the plate shows that velocity increases rapidly near the plate and after attaining a maximum value, it decreases as y increases.

Figs 9-16 shows the effects of various parameters such as Pr, Sc, S, Nr, K, M, ω, Gr and Gm, when the plate is heated by free-convection currents (Gr<0).). It is noticed that the velocity decreases with increase of Schmidt number(Sc), Radiation parameter (Nr), Hartmann number (M), Oscillating frequency(ω),whereas increases with the increase of Prandtl number(Pr),Sink strength (S), Chemical reaction parameter (K), Grashoff number (Gr), modified Grashoff number (Gm).

Temperature profiles: The temperature profiles are depicted in Figs 17-18.

Figure-(17) shows the effects of the parameters Pr,Nr,ω on temperature profile at any point of the fluid, when S=0.5, ε=0.02,n=0.5,t=1.0. It is noticed that the temperature falls for the increase of Prandtl number(Pr),Oscillating frequency (ω), but rises in the increase of Radiation parameter (Nr).

Figure-(18) shows the effects of the parameter S on temperature profile at any point of the fluid, when Pr=0.72, Nr=0.5,ω=0.3, ε=0.02,n=0.5,t=1.0. It is noticed that the temperature falls for the increase of Sink strength (S).

Concentration profiles: The concentration profiles are depicted in Figs 19 only.

Figure-(19) shows the effects of the parameters Sc, K, ω on concentration profile at any point of the fluid, when ε=0.02, n=0.5,t=1.0. It is noticed that the concentration decreases with increase of Schmidt number (Sc) and Chemical reaction parameter (K),whereas increases with increase of Oscillating frequency(ω).

It is noticed that Oscillating frequency effect on the temperature and concentration boundary layers.

Shearing stress of mean velocity: The shearing stresses of velocity are depicted in Tables 1-2.

Table-(1) shows the effects of various parameters Pr, Sc, S, Nr, K, M, ω, Gr and Gm on shearing stress of velocity for the cooling of the plate (Gr>0) at any point of fluid ,when $\varepsilon=0.02$, n=0.5, t=1.0. It is observed that the shearing stress at plate decreases with increase of Prandtl number(Pr), Schmidt number (Sc), Sink strength (S), Chemical reaction parameter (K), Hartmann number (M), Oscillating frequency(ω), whereas increases with the increase of Radiation parameter (Nr), Grashoff number (Gr), modified Grashoff number (Gm).

Table-(2) shows the effects of various parameters Pr, Sc, S, Nr, K, M, ω, Gr and Gm on shearing stress of velocity for the heating of the plate (Gr<0) at any point of fluid, when $\varepsilon=0.02$, n=0.5, t=1.0. It is observed that the shearing stress at the plate increases with increase of Prandtl number(Pr), Sink strength (S), Chemical reaction parameter (K), modified Grashoff number (Gm),whereas decreases with the increase of Schmidt number (Sc), Radiation parameter (Nr), Hartmann number (M), Grashoff number (Gr), Oscillating frequency(ω).

Nusselt number: The Nusselt number of temperature is depicted in Table-3. It shows the effect of the parameters Pr,S,Nr,ω rate of heat transfer at upper and lower plates, when $\varepsilon=0.02$, n=0.5, t=1.0. It is observed that the rate of heat transfer decreases with increase of Prandtl number (Pr), Sink strength (S), Oscillating frequency (ω), where as increases with the increase of Radiation parameter (Nr).

Sherwood number: The Sherwood number of mass concentration is depicted in Table-4. It shows the effect of the parameters Sc, K, ω rate of mass transfer at upper and lower plates, when $\varepsilon=0.02$, n=0.5, t=1.0. It is observed that the rate of mass transfer decreases with increase of Schmidt number(Sc), Chemical reaction parameter (K), whereas increases with the increase of Oscillating frequency(ω).

5. CONCLUSIONS

The combined effect of chemical reaction, heat and mass transfer on an unsteady MHD free convective flow embedded in a porous medium with heat generation have been discussed. The equations governing such flow are transformed to dimensionless form. The ultimate resulting resulting equations obtained are solved using multi parameter Perturbation method. The results are shown graphically for different values of parameters considered in the analysis. The present investigation can be concluded as follows:

- The velocity of the fluid decreases with increase of Pr, Sc, S, M, ω on cooled plate, Also it increases with increase of K, Nr, Gr, Gm.
- The velocity of the fluid decreases with increase of Sc, Nr, M, ω on heated plate, Also it increases with increase of Pr, S, K, Gr, Gm.
- Velocity field is considerably affected for the values of Pr, S, Nr.
- Pr, ω, S effects lowered the temperature of the fluid.
- The concentration of the fluid decreases with increase of Sc and K, Also it increases with increase of ω.
- Effects ω on both temperature and concentration in boundary layer.
- The skin friction of the fluid decreases with increase of Pr, Sc, S, K, M, ω on cooled plate, Also increases with increase of Nr, Gr, Gm.
- The skin friction of the fluid increases with increase of Pr, S, K, Gm on heated plate, Also decreases with increase of Sc, Nr, M, Gr, ω.
- Effects ω on both Nusselt number and Sherwood number.

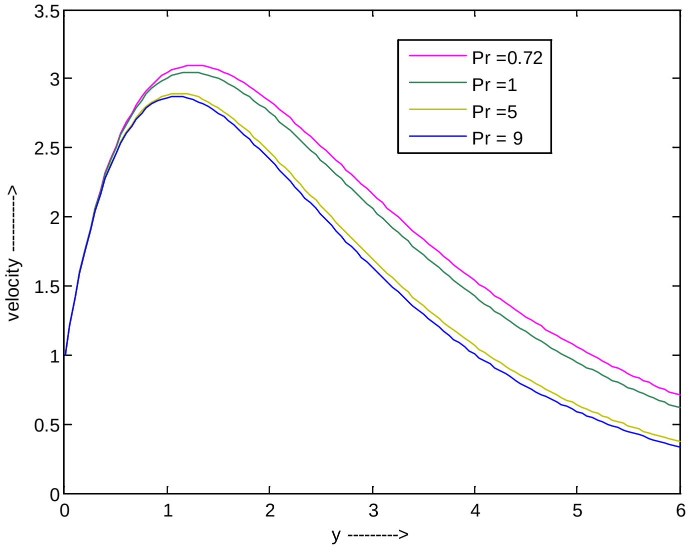

Figure-(1): Effect of Pr on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Sc=0.22, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

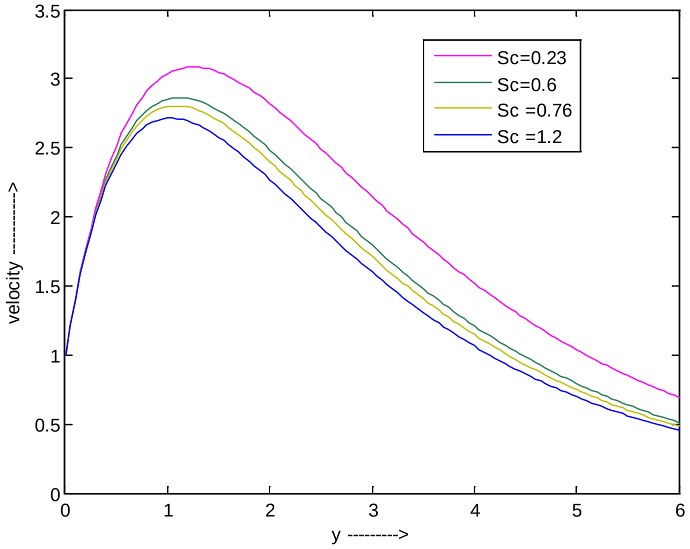

Figure-(2): Effect of Sc on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Pr=0.72, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

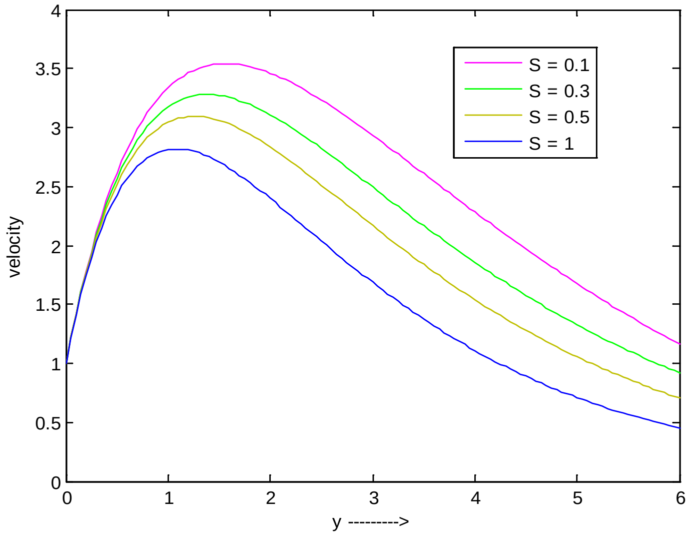

Figure-(3): Effect of S on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Pr=0.72, Sc=0.22, ω=0.3, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

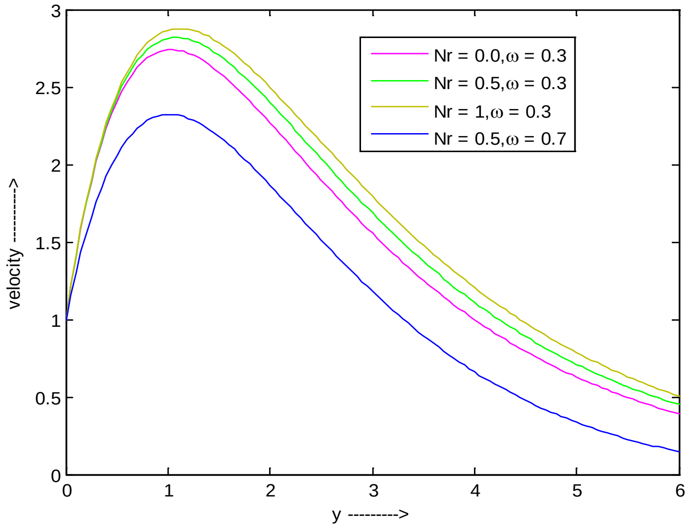

Figure-(4): Effect of Nr and ω on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Pr=0.72, Sc=0.22, S=1, M=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

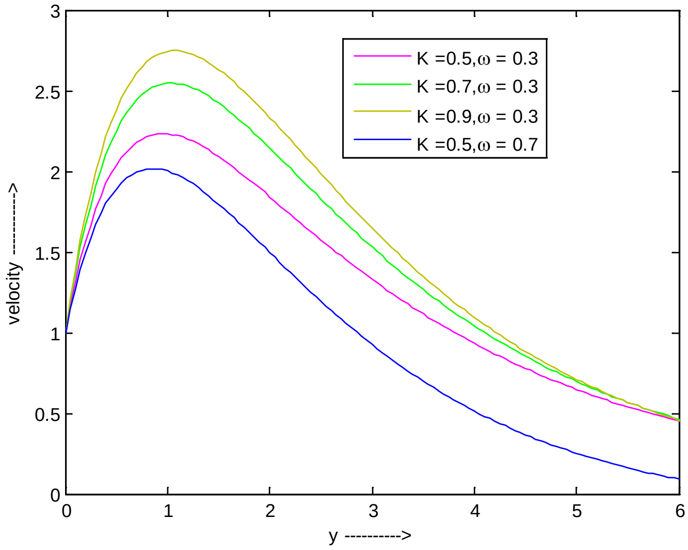

Figure-(5): Effect of K and ω on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Pr=0.72, Sc=0.22, S=1, M=0.5, Nr=0.5, ε=0.02, n=0.5, t=1.0.

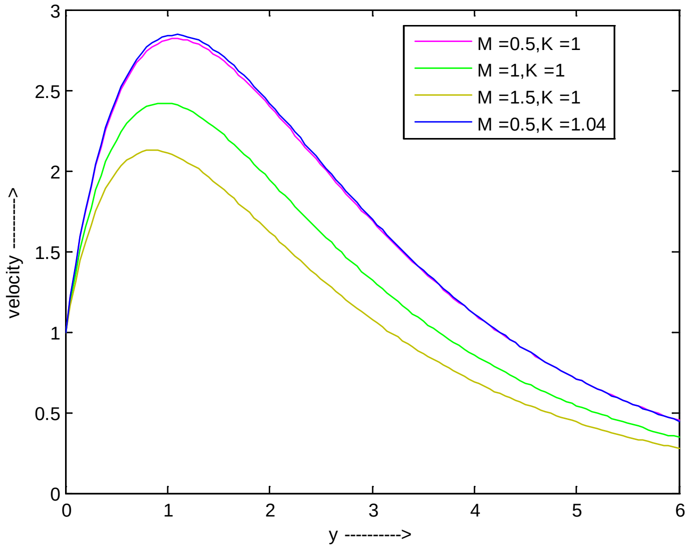

Figure-(6): Effect of M and K on velocity profile u for cooling of the plate, when Gr=5, Gm=5, Pr=0.72, Sc=0.22, ω=0.3, S=1, Nr=0.5, ε=0.02, n=0.5, t=1.0.

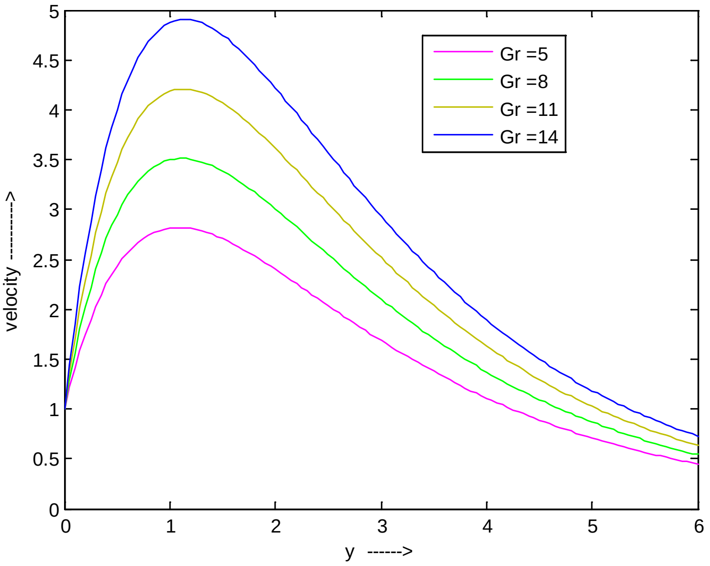

Figure-(7): Effect of Gr on velocity profile u for cooling of the plate, when Gm=5, Pr=0.72, Sc=0.22, ω=0.3, S=1, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

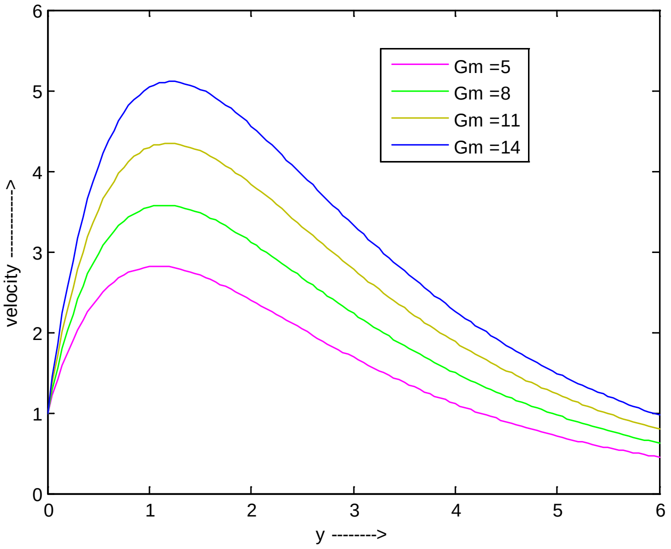

Figure-(8): Effect of Gm on velocity profile u for cooling of the plate, when Gr=5, Pr=0.72, Sc=0.22, ω=0.3, S=1, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

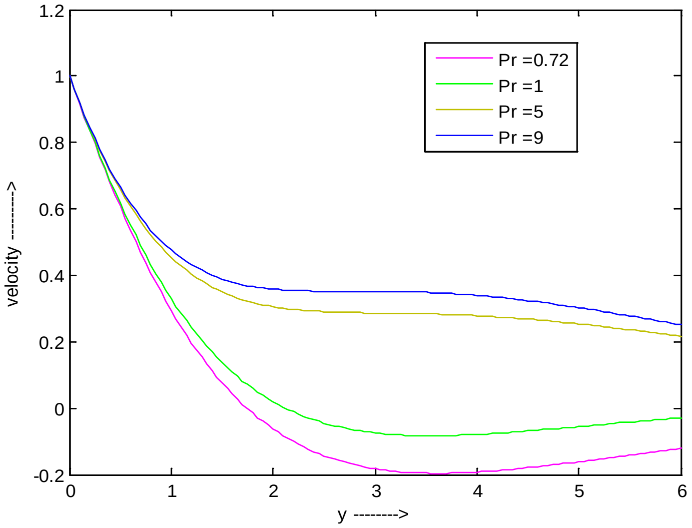

Figure-(9): Effect of Pr on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Sc=0.22, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

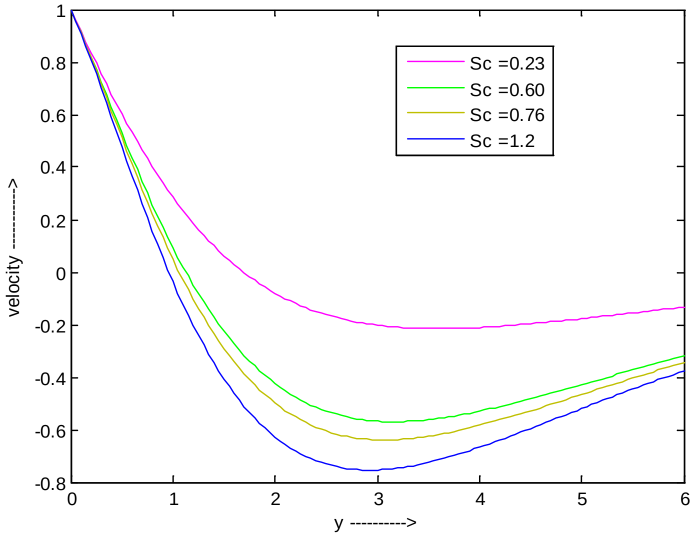

Figure-(10): Effect of Sc on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Pr=0.72, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5,t=1.0.

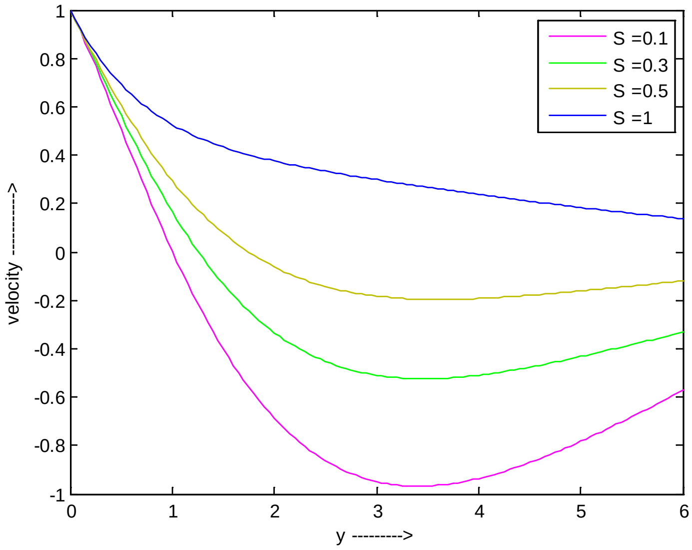

Figure-(11): Effect of S on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Pr=0.72, Sc=0.22, ω=0.3, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

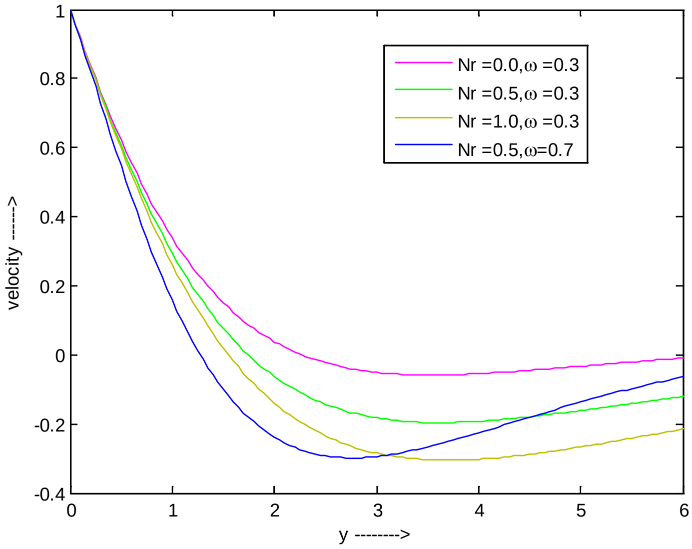

Figure-(12): Effect of Nr and ω on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Pr=0.72, Sc=0.22, S=0.5, M=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

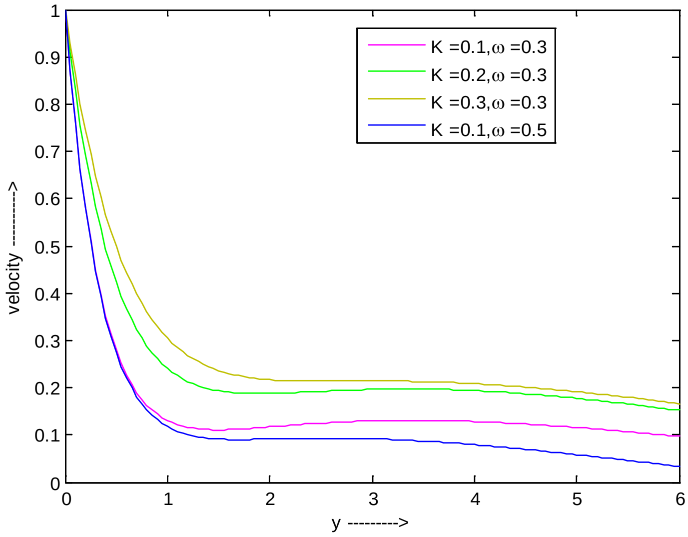

Figure-(13): Effect of K and ω on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Pr=0.72, Sc=0.22, S=0.5, M=0.5, Nr=0.5, ε=0.02, n=0.5, t=1.0.

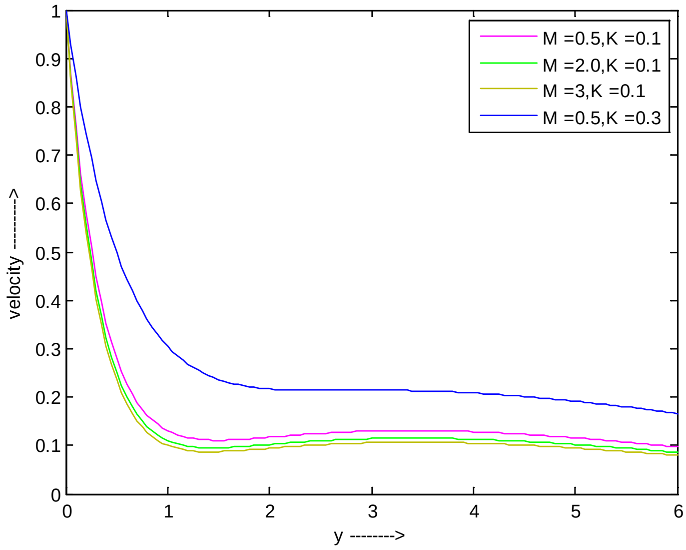

Figure-(14): Effect of M and K on velocity profile u for heating of the plate, when Gr=-5, Gm=5, Pr=0.72, Sc=0.22, ω=0.3, S=0.5, Nr=0.5, ε=0.02, n=0.5, t=1.0.

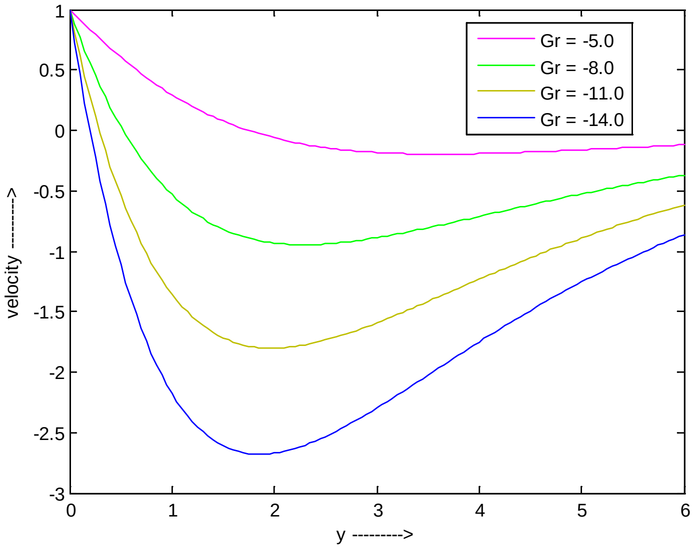

Figure-(15): Effect of Gr on velocity profile u for heating of the plate, when Gm=5, Pr=0.72, Sc=0.22, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

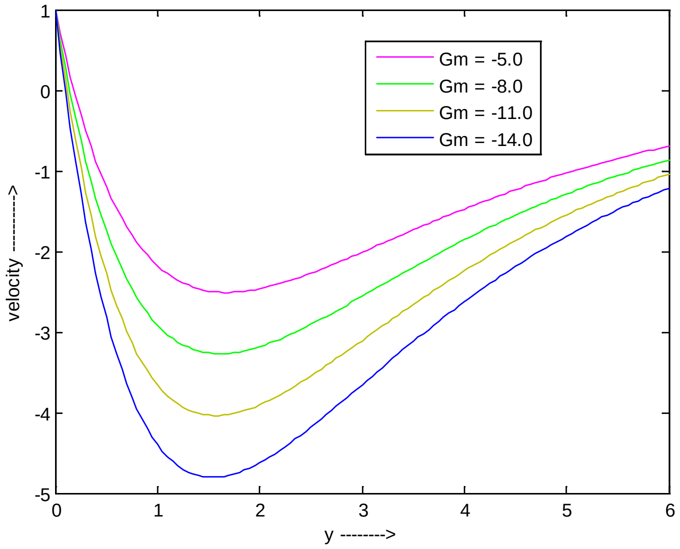

Figure-(16): Effect of Gm on velocity profile u for heating of the plate, when Gr=-5, Pr=0.72, Sc=0.22, ω=0.3, S=0.5, M=0.5, Nr=0.5, K=1.0, ε=0.02, n=0.5, t=1.0.

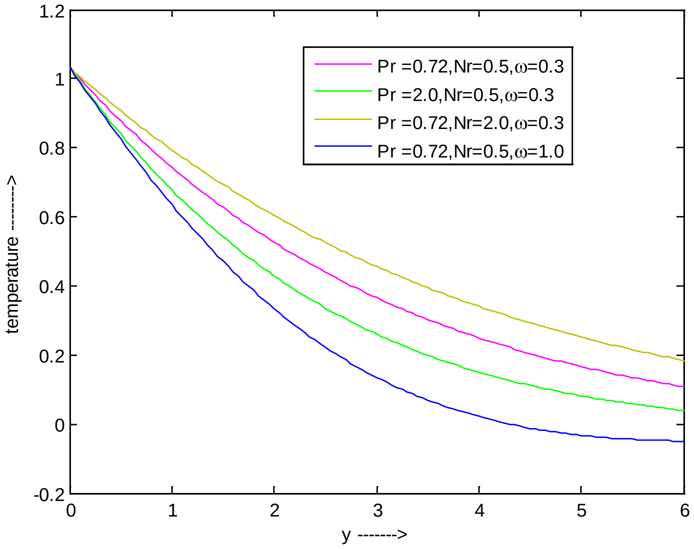

Figure-(17): Effect of Pr, Nr and ω on temperature profile, when S=0.5, ε=0.02, n=0.5, t=1.0.

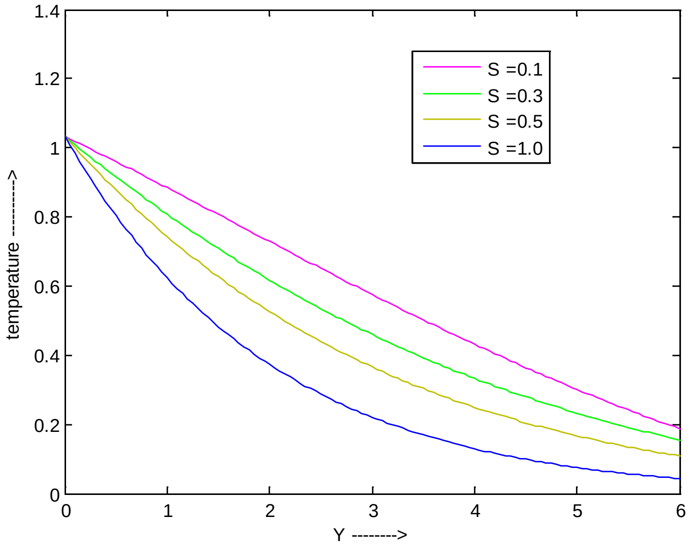

Figure-(18): Effect of S on temperature profile, when Pr=0.72, Nr=0.5, ω=0.3, ε=0.02, n=0.5, t=1.0.

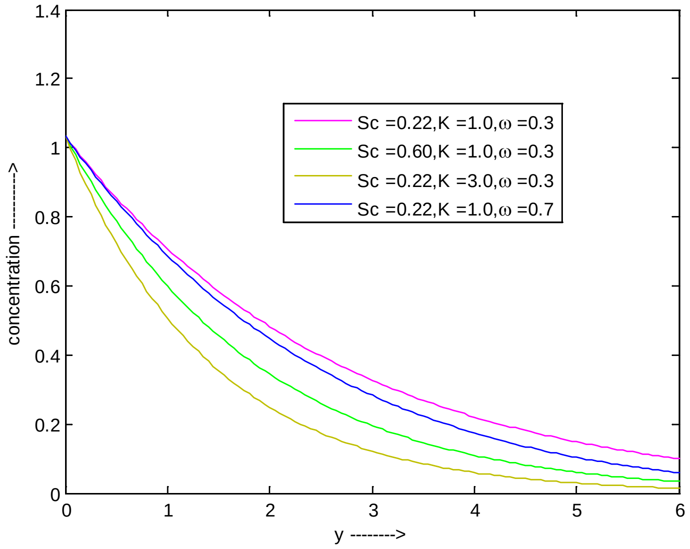

Figure-(19): Effect of Sc, K and ω on concentration profile, when ε=0.02, n=0.5, t=1.0.

Table-1: Skin friction coefficient (τ) for cooling of the plate (Gr >0)

Pr	Sc	S	Nr	K	M	Gr	Gm	ω	τ
0.72	0.22	0.5	0.5	1.0	0.5	5	5	0.3	2.3651
5.0	0.22	0.5	0.5	1.0	0.5	5	5	0.3	1.8497
0.72	0.60	0.5	0.5	1.0	0.5	5	5	0.3	1.8056
0.72	0.22	1.0	0.5	1.0	0.5	5	5	0.3	1.7924
0.72	0.22	0.5	1.0	1.0	0.5	5	5	0.3	2.4601
0.72	0.22	0.5	0.5	1.04	0.5	5	5	0.3	2.3321
0.72	0.22	0.5	0.5	1.0	1.0	5	5	0.3	2.3056
0.72	0.22	0.5	0.5	1.0	0.5	8	5	0.3	3.3666
0.72	0.22	0.5	0.5	1.0	0.5	5	8	0.3	3.2793
0.72	0.22	0.5	0.5	1.0	0.5	5	5	0.7	1.9027

Table-2: Skin friction coefficient (τ) for heating of the plate (Gr <0)

Pr	Sc	S	Nr	K	M	Gr	Gm	ω	τ
0.72	0.22	0.5	0.5	1.0	0.5	-5	5	0.3	-0.9732
5.0	0.22	0.5	0.5	1.0	0.5	-5	5	0.3	-0.4578
0.72	0.60	0.5	0.5	1.0	0.5	-5	5	0.3	-1.5327
0.72	0.22	1.0	0.5	1.0	0.5	-5	5	0.3	-0.4005
0.72	0.22	0.5	1.0	1.0	0.5	-5	5	0.3	-1.0682
0.72	0.22	0.5	0.5	1.04	0.5	-5	5	0.3	-0.9902
0.72	0.22	0.5	0.5	1.0	1.0	-5	5	0.3	-1.1220
0.72	0.22	0.5	0.5	1.0	0.5	-8	5	0.3	-1.9746
0.72	0.22	0.5	0.5	1.0	0.5	-5	8	0.3	-0.0590
0.72	0.22	0.5	0.5	1.0	0.5	-5	5	0.7	-0.7552

Table-3: Heat transfer coefficient in terms of Nusselt number(Nu)

Pr	S	Nr	ω	Nu
0.72	0.5	0.5	0.3	-0.3310
4.0	0.5	0.5	0.3	-0.4595
0.72	1.0	0.5	0.3	-0.5161
0.72	0.5	1.0	0.3	-0.3044
0.72	0.5	0.5	0.7	-0.3832

Table-4: Mass transfer coefficient in terms of Sherwood number(Sh)

Sc	K	ω	Sh
0.23	1.0	0.3	-0.3956
0.60	1.0	0.3	-0.5553
0.23	2.0	0.3	-0.5937
0.23	1.0	0.7	-0.4154

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