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Transient natural convection magnetohydrodynamic motion over an exponentially accelerated vertical porous plate with heat source

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Effects of heat source on the magnetohydrodynamic (MHD) one-dimensional flow past a vertical surface have been analyzed. Thermal radiation effect is present. The Laplace transformation procedure reduces the involved governing PDEs into the ODEs and hence closed form solutions have been obtained. The effect of permeability parameter (k), heat source parameter (Q), thermal radiation (R), suction parameter (γ), magnetic field parameter (M) have been analyzed on the velocity and temperature distributions, Skin friction coefficient (τ) and Nusselt number (Nu). The convergence of the obtained solutions has been seen through graphical results. Effects of skin friction (τ) and the Nusselt number (Nu) for different parameters have also been analyzed.

Keywords: Thermal radiation, MHD flow, Porous medium, Heat source, Vertical porous plate

1 Introduction

The report of unsteady free convection motion of viscous incompressible liquid over vertical surfaces has vast engineering and technological applications. Natural convective motions arises at high temperature, the impacts of radiation are significant importance. Thermal radiation leads to various basic phenomena nearby us, from solar radiation to fire incandescent lamp, and has acted a vital character in combustion and furnace design, cooling of towers, gas turbines, design of fins, nuclear power plants and many propulsion device for aircraft, temperature measurements, energy utilization, remote sensing for astronomy and space exploration.

Magnetohydrodynamic (MHD) motion and transfer of heat and mass operation arise in various industrial applications including the aerodynamic processes, electromagnetic pumps, geothermal system, MHD power generators, chemical catalytic reactors and processes. Numerous investigations have been performed to explore the MHD transient natural convection motion. Gupta[1] has investigated the influence of magnetic field on transient natural convective of an electrically conducting liquid past a heated vertical sheet. It is observed that the influence of magnetic field is to lessen the rate of heat transfer from the wall. Khan *et al.*[2] have studied the mixed convection of heat and mass transfer on unsteady MHD free convective motion past a vertical sheet under the influence of effect of radiation immersed in a permeable medium. It is noted that the velocity descriptions of fluid reduce with enhancing shear stress. Muthucumaraswamy *et al.*[3] have analyzed the unsteady motion over a vertical sheet under the influence of variable mass diffusion and surface temperature. Rajesh and Chamkha[4] have analyzed the unsteady convective motion over a vertical permeable sheet under the influence of Newtonian heating and viscous dissipation. Siddique and Mirza[5] have investigated the influence of heat source on unsteady MHD heat and mass transfer of a natural convective motion of a viscoelastic liquid with permeable medium. El-Aziz and Yahya[6] have studied the combined impacts of thermal and concentration distributions on unsteady MHD natural convective motion over a moving sheet immersed in a permeable medium. Das *et al.*[7] have analyzed the effect of thermal radiation on transient free convection motion of optically thick radiating liquid over a rotating vertical sheet under the influence of ramped heat and mass fluxes. Raju *et al.*[8] have reported the impact of magnetic field and chemical reaction on unsteady viscous fluid motion over a vertical sheet in the presence of heat source. Turkyilmazoglu and Pop[9] have considered the impact of thermodiffusion, radiation and heat absorption/generation on magnetohydrodynamic

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natural convective motion over a vertical sheet. Noor *et al.*[10] have examined the natural convective MHD motion past a radiative isothermal porous plat with thermophoretic and heat source/sink effects. Zueco *et al.*[11] have explored the numerical solution of two dimension unsteady natural convection transfer of heat and mass motion past a infinite vertical sheet under the influence of induced magnetic field and Soret effect. Mishra *et al.*[12] have studied the impact of transfer of mass and heat on natural convection magnetohydrodynamic motion of a visco-elastic incompressible electrically conducting liquid over a vertical permeable sheet via a permeable medium in the presence of a uniform transverse magnetic field and heat source. Sahin Ahmed *et al.*[13] have analyzed the perturbation solution of a MHD steady combined convection motion of a chemically reacting liquid past a vertical permeable sheet. It is noticed that velocity decreases with enhance in Hartmann or magnetic Prandtl number even if the temperature is observed to be clearly raised with an enhancement in the Hartmann number (*M*) or chemical reaction parameter (*K*). An enhancement in heat source/sink or chemical reaction is observed to increase induced magnetic field while an enhancement in *M* or magnetic Prandtl number (*Pr*) is presented to expend the reverse impact. Hernández and Zueco[14] have examined the effects of radiation, chemical reaction and mass flux on unsteady MHD natural convection flow past a vertical porous sheet. Rout *et al.*[15] have analyzed the magnetohydrodynamic motion over a vertical sheet in a floating temperature under the influence of chemical reaction and heat source. Das[16] has studied the flow of mass and heat transfer on magnetohydrodynamic micropolar liquid in a revolving structure of source under the influence of thermal radiation and heat source. Khan *et al.*[17] have examined the numerical study of heat generation/absorption fact in Falkner-Skan wedge motion of Carreau nanofluid under the influence of Brownian motion and thermophoresis effects. Ahmed *et al.*[18] have explored the analytical and numerical interpretation for MHD three dimensional motion via two equidistant permeable sheets. Mishra *et al.*[19] have investigated the effect of heat source on magnetohydrodynamic motion over a stretching surface under the influence of non-Darcy porous medium. Sharma *et al.*[20] have studied the impact of radiation and heat generation on transient natural convection magnetohydrodynamic motion of a nanofluid over a vertical sheet.

The main aim of the current investigation is to examine the impacts of heat source and thermal radiation on unsteady MHD free convection heat transfer motion of a viscous fluid over a vertical sheet. The governing equations are solved analytically using Laplace transform technique. Numerical results are reported for various values of the physical parameters of interest.

2 Mathematical Analysis

An unsteady 1-D natural convection flow of a viscous incompressible liquid over a vertical sheet in a porous medium with variable temperature is considered. The x-axis is being taken vertically upwards along the vertical plate and *y*- axis is taken to be normal to the plate. The physical model and coordinate system of the flow problem is shown in Fig. 1.

Initially, it is considered that the sheet and liquid are at the same temperature T'_∞ in the stationary condition. At $t' \geq 0$, the sheet is exponentially accelerated with a velocity $u' = u'_0 \exp(a't')$ in its own plane and the plate temperature is raised linearly with time *t*. A uniform magnetic field (M) is applied in the direction perpendicular to the plate. The fluid is assumed to be slightly conducting, so that the magnetic Reynolds number is much less than unity and hence the induced magnetic field is negligible in comparison with the applied magnetic field. The fluid considered here is a gray, absorbing/emitting radiation

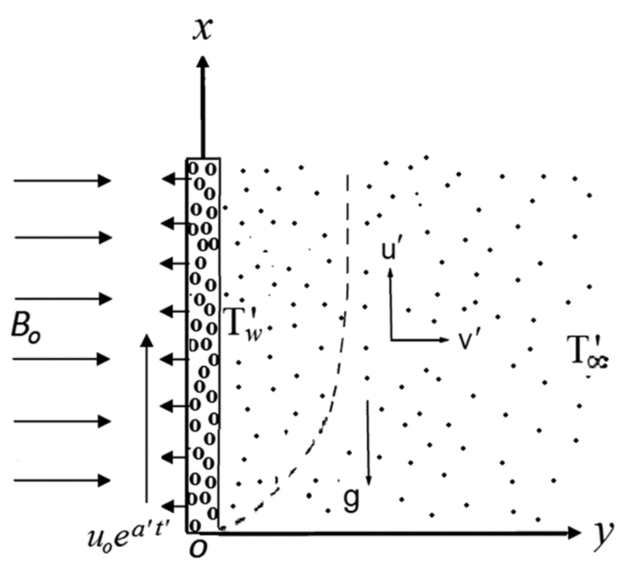

Fig. 1 – Physical configuration of the flow model.

but a non-scattering medium. The viscous dissipation is also assumed to be negligible in the energy equation as the motion is due to natural convection only. It is also assumed that all the fluid properties are constant except for the density in the buoyancy term, which is given by the usual Boussinesq's approximation. With the above assumptions, the governing equations for one-dimensional flow of a viscous incompressible fluid are expressed as:

$$\frac{\partial u'}{\partial t'}+\mathrm{v}'\frac{\partial u'}{\partial y'}=\nu\frac{\partial^2 u'}{\partial y'^2}+g\beta\left(T'-T'_\infty\right)-\frac{\sigma B_0^2}{\rho}u'-\frac{\nu}{k'}u' \quad ...(1)$$

$$\rho C_p\left(\frac{\partial T'}{\partial t'}+\mathrm{v}'\frac{\partial T'}{\partial y'}\right)=\kappa\frac{\partial^2 T'}{\partial y'^2}-\frac{\partial q_r}{\partial y'}+Q_0\left(T'-T'_\infty\right) \quad ...(2)$$

The corresponding initial and boundary conditions are:

$$\left.\begin{array}{llll} t'\le 0: & u'=0, & T'=T'_\infty & \forall \ y' \\ t'>0: & u'=u_0\exp(a't'), & T'=T'_\infty+\left(T'_w-T'_\infty\right)At' & \text{at } \ y'=0 \\ & \mathrm{u}'\to 0, & T'\to T'_\infty & \text{as } \ y\to\infty \end{array}\right\} \quad ...(3)$$

where $A=\frac{u_0^2}{\nu}$

The local radiant for the case of an optically thin gray gas is expressed by:

$$\frac{\partial q_r}{\partial y'}=-4a^*\sigma\left(T'^4_\infty-T'^4\right) \quad ...(4)$$

It is assume that the temperature differences within the flow are sufficiently small such that T'^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T'^4 in a Taylor series about T'_∞ and neglecting higher-order terms, thus:

$$T'^4=4T'^3_\infty T'-3T'^4_\infty \quad ...(5)$$

By using Eqs (4) and (5), Eq. (2) gives:

$$\rho C_p\left(\frac{\partial T'}{\partial t'}+\mathrm{v}'\frac{\partial T'}{\partial y'}\right)=\kappa\frac{\partial^2 T'}{\partial y'^2}-16a^*\sigma T'^3_\infty\left(T'_\infty-T'\right)+Q_0\left(T'-T'_\infty\right) \quad ...(6)$$

On introducing the following non-dimensional quantities:

$$\left.\begin{array}{llll} U=\frac{u'}{u_0}, & Y=\frac{y'u_0}{\nu}, & t=\frac{t'u_0^2}{\nu}, & T=\frac{T'-T'_\infty}{T'_w-T'_\infty} \\ \Pr=\frac{\mu C_p}{\kappa}, & Gr=g\beta\ \nu\frac{T'_w-T'_\infty}{u_0^3}, & & M=\frac{\sigma B_0^2 r_0^2}{\nu\rho} \\ k=\frac{k'u_0^2}{\nu^2}, & R=\frac{16a^*\nu^2\sigma T'^3_\infty}{\kappa\ u_0^2}\ , & a=\frac{a'\nu}{u_0^2}, & \gamma=-\frac{\mathrm{v}'}{u_0} \\ Q=\frac{\nu^2 Q_0}{\kappa u_0^2}, r_0=\frac{\nu}{u_0} & & & \end{array}\right\} \quad ...(7)$$

The governing Eqs (1) and (6) reduce to:

$$\frac{\partial U}{\partial t}-\gamma\frac{\partial U}{\partial Y}=\frac{\partial^2 U}{\partial Y^2}+GrT-MU-\frac{U}{k} \quad ...(8)$$

$$\frac{\partial T}{\partial t}-\gamma\frac{\partial T}{\partial Y}=\frac{1}{\Pr}\frac{\partial^2 T}{\partial Y^2}-\frac{R}{\Pr}T+\frac{Q}{\Pr}T \quad ...(9)$$

And the corresponding initial and boundary conditions are:

$$\left.\begin{array}{llll} t\le 0: & U=0, & T=0, & \forall \ \ Y \\ t>0: & U=Exp(at), & T=t, & \text{at } \ Y=0 \\ & U\to 0, & T\to 0, & \text{as } \ Y\to\infty \end{array}\right\} \quad ...(10)$$

3 Solution Technique

The dimensionless governing Eqs (8) and (9), subject to the initial and boundary conditions (10), are solved by the usual Laplace-transform technique and the solutions are derived as follows:

$$\frac{d^2\overline{U}}{dY^2}+\gamma\frac{d\overline{U}}{dY}-\left(p+M+\frac{1}{k}\right)\overline{U}+Gr\overline{T}=0 \quad ...(11)$$

$$\frac{d^2\overline{T}}{dY^2}+\gamma\frac{d\overline{T}}{dY}-\left(p+R-Q\right)\overline{T}=0 \quad ...(12)$$

where p is the Laplace transformation parameter and $\overline{U}$ & $\overline{T}$ are the Laplace transform of U and T, respectively.

Solution of Eqs (11) and (12) subject to the boundary conditions in (10) gives:

$$\overline{U}=\frac{1}{p-a}e^{-Y\left(\frac{\gamma}{2}+\sqrt{p+B}\right)}+\frac{Gr}{A\,p^2}e^{-Y\left(\frac{\gamma}{2}+\sqrt{p+B}\right)}-\frac{Gr}{A\,p^2}e^{-Y\left(\frac{\gamma}{2}+\sqrt{p+\frac{\gamma^2}{4}+R-Q}\right)} \quad ...(13)$$

$$\overline{T}=\frac{1}{p^2}e^{-Y\left(\frac{\gamma}{2}+\sqrt{p+\frac{\gamma^2}{4}+R-Q}\right)} \quad ...(14)$$

$$A=R-Q-M-\frac{1}{k},\qquad \mathrm{B}=\frac{\gamma^2}{4}+M+\frac{1}{k},\qquad D=\frac{\gamma^2}{4}+R-Q$$

Taking the inverse Laplace transforms of Eqs (13) and (14), we have:

$$\begin{aligned} U=\frac{e^{at}}{2}&\left\{e^{-Y\left(\frac{\gamma}{2}+\sqrt{a+B}\right)}erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{(a+B)t}\right)+e^{-Y\left(\frac{\gamma}{2}-\sqrt{a+B}\right)}erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{(a+B)t}\right)\right\} \\ &+\frac{Gr}{A}\left(\frac{t}{2}-\frac{Y}{4\sqrt{B}}\right)\exp\left(-Y\left(\frac{\gamma}{2}+\sqrt{B}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{Bt}\right) \\ &+\frac{Gr}{A}\left(\frac{t}{2}+\frac{Y}{4\sqrt{B}}\right)\exp\left(-Y\left(\frac{\gamma}{2}-\sqrt{B}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{Bt}\right) \\ &-\frac{Gr}{A}\left(\frac{t}{2}-\frac{Y}{4\sqrt{D}}\right)\exp\left(-Y\left(\frac{\gamma}{2}+\sqrt{D}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{Dt}\right) \\ &-\frac{Gr}{A}\left(\frac{t}{2}+\frac{Y}{4\sqrt{D}}\right)\exp\left(-Y\left(\frac{\gamma}{2}-\sqrt{D}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{Dt}\right) \end{aligned} \quad ...(15)$$

$$T=\left(\frac{t}{2}-\frac{Y}{4\sqrt{D}}\right)\exp\left(-Y\left(\frac{\gamma}{2}+\sqrt{D}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{D\,t}\right)+\left(\frac{t}{2}+\frac{Y}{4\sqrt{D}}\right)\exp\left(-Y\left(\frac{\gamma}{2}-\sqrt{D}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{D\,t}\right) \quad ...(16)$$

The physical quantity of interest, in non-dimensional form the skin friction and Nusselt number are:

$$\tau=-\left.\frac{\partial U}{\partial Y}\right]_{Y=0} \quad ...(17)$$

$$Nu=-\left.\frac{\partial T}{\partial Y}\right]_{Y=0} \quad ...(18)$$

3.1 Skin friction

The expressions for the skin-friction:

$$\tau=\frac{e^{-Bt}}{\sqrt{\pi\,t}}+\frac{e^{at}}{2}\left\{\left(\frac{\gamma}{2}+\sqrt{a+B}\right)erfc\left(-\sqrt{t(a+B)}\right)+\left(\frac{\gamma}{2}-\sqrt{a+B}\right)erfc\left(\sqrt{t(a+B)}\right)\right\}+\frac{Gr\,t}{2A}\left\{\left(\frac{\gamma}{2}+\sqrt{B}\right)erfc\left(-\sqrt{B\,t}\right)+\left(\frac{\gamma}{2}-\sqrt{B}\right)erfc\left(\sqrt{B\,t}\right)\right\}+\frac{Gr\,t}{2A}\left\{\left(\frac{\gamma}{2}+\sqrt{D}\right)erfc\left(-\sqrt{D\,t}\right)+\left(\frac{\gamma}{2}-\sqrt{D}\right)erfc\left(\sqrt{D\,t}\right)\right\}+\frac{Gr}{4A\sqrt{B}}\left\{erfc\left(-\sqrt{B\,t}\right)-erfc\left(\sqrt{B\,t}\right)\right\}-\frac{Gr}{4A\sqrt{D}}\left\{erfc\left(-\sqrt{D\,t}\right)-erfc\left(\sqrt{D\,t}\right)\right\}+\frac{Gr\sqrt{t}}{A\sqrt{\pi}}\left\{e^{-Bt}-e^{-Dt}\right\} \quad ...(19)$$

3.2 Nusselt number

The expression for Nusselt number:

$$Nu=\frac{t}{2}\left\{\left(\frac{\gamma}{2}+\sqrt{D}\right)erfc\left(-\sqrt{D\,t}\right)+\left(\frac{\gamma}{2}-\sqrt{D}\right)erfc\left(\sqrt{D\,t}\right)\right\}-\frac{1}{4\sqrt{D}}\left\{erfc\left(-\sqrt{D\,t}\right)-erfc\left(\sqrt{D\,t}\right)\right\}+\sqrt{\frac{t}{\pi}}\,e^{-Dt} \quad ...(20)$$

4 Results and Discussion

In order to understand the physical insight into the problem, numerical values of velocity, temperature, skin-friction and Nusselt number are obtained for different values of the physical parameters and they are presented in graphs (Fig. 2 – Fig. 14).

The effect of permeability parameter on the transient velocity profiles is shown in Fig. 2 at *a*=0.4, *Gr* = 4, γ=0.6, *M*=1.5, *Q*=1.5, *R*=1, *t*=0.4. It can be observed from the figure, that the velocity increases for increase in permeability parameter. Figure 3 on the other hand shows the effect of heat source/sink parameter on velocity profiles at *a*=0.6, *Gr* = 6, γ=0.3, *M*=1.5, *k*= 0.5, *R*=2, *t*=0.8. With increase in positive *Q* (heat source) the fluid velocity increases, whereas as with increase in negative value of *Q* (heat sink) the fluid velocity decreases. This is due to the fact that positive value of *Q* (heat source) generates heat and hence enhances the buoyancy force and thus increases the velocity of the fluid. Effect of radiation on velocity profile against non dimensional distance *Y* is depicted in Fig. 4. It is observed from the figure that velocity decreases with increase in radiation. Effect of suction parameter on velocity profile for negative and positive values of Grashof number is shown in Fig. 5. The figures shows that the velocity decreases with increase in suction parameter for the both the case of positive Grashof number (heating of porous plate) and negative Grashof number (cooling of porous plate). Effect of magnetic field parameter for different values of time on velocity profile is shown in Fig. 6 at *a*=0.4, *Gr*=5, *Q*=1.5, γ = 0.5, *k* =0.6, *R*=2. The figure reveals that velocity decreases with increase in Magnetic field parameter. It is obvious as the application of transverse magnetic field results a resistive type force

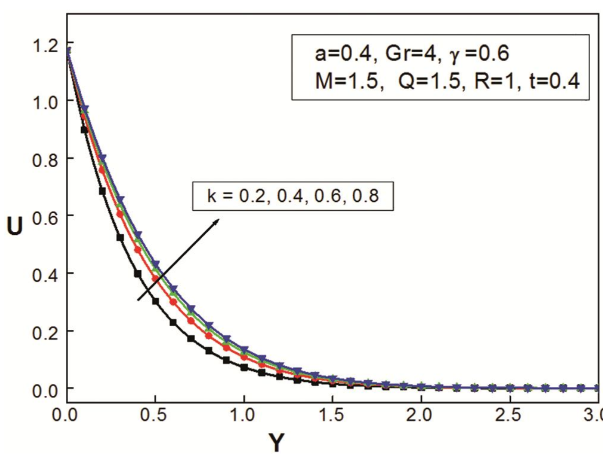

Fig. 2 – Velocity profile for different values of *k*.

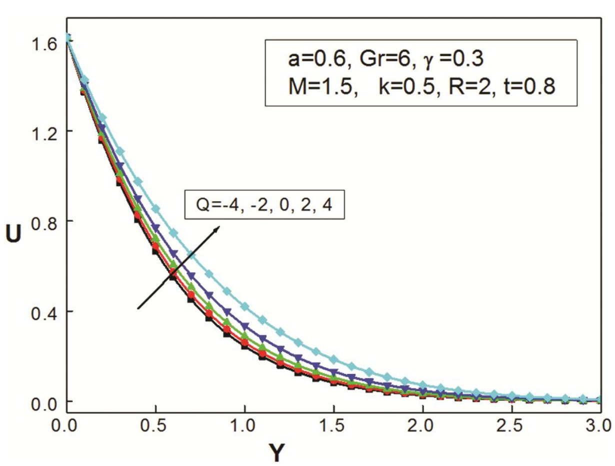

Fig. 3 – Velocity profile for different values of heat source parameter *Q*.

which reduces the fluid velocity. Also, transient fluid velocity increases with increase in time. Effect of heat source/sink on temperature profile is shown in Fig. 7 at γ = 0.6, R=1.5, t=0.6. The figure clearly shows that temperature increases with increase in heat source and decreases with increase in heat sink. Effects of suction parameter and radiation parameter are shown in Fig. 8 and Fig. 9, respectively. These figures show that temperature decreases with increased values of suction parameter as well as radiation parameter. Effect of heat source/sink on skin friction against time is shown in Fig. 10 at a=0.4, Gr=6, γ = 0.4, M=1.5, k= 0.6, R=2. Figure 11 on the other hand shows the effect of magnetic field on skin friction. It can be observed from both the figures that, initially skin friction decreases very fast with time, but after some time the rate decrease of skin friction slows down. Skin friction decreases with increase in heat source but increases with increase in heat sink. Also, skin friction increases with increase in Magnetic field effect. Effect of permeability for both positive and negative Grashof numbers on skin friction is depicted in Fig. 12. This shows that skin friction increases with decreased values of permeability parameter. Effect of

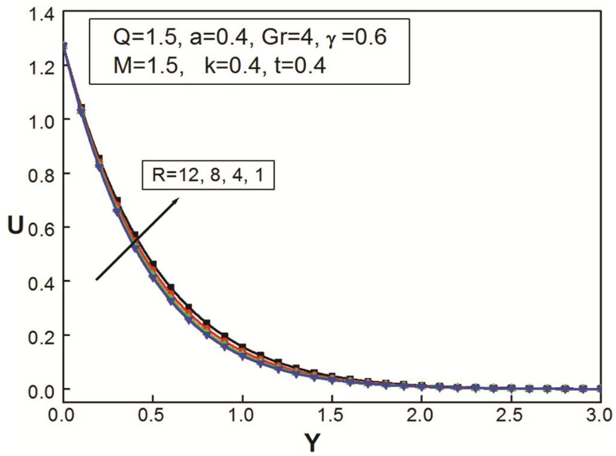

Fig. 4 – Velocity profile for different values of radiation parameter R.

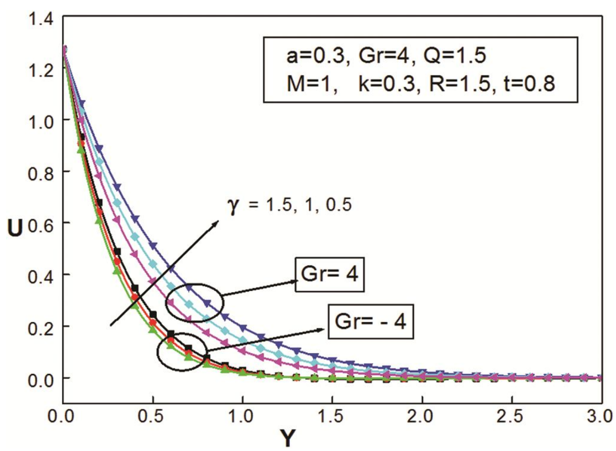

Fig. 5 – Velocity profile for different values of suction parameter at Gr = - 4 and 4.

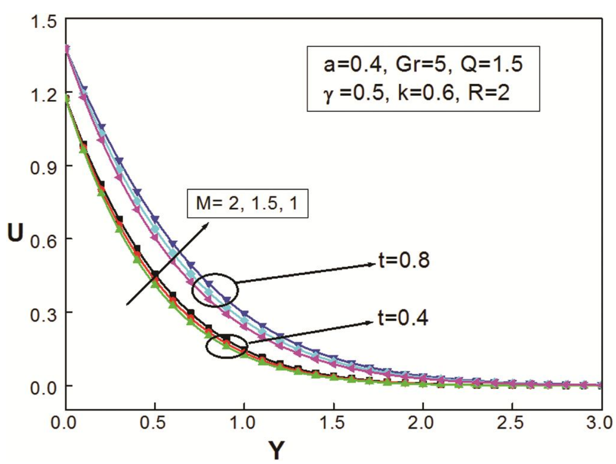

Fig. 6 – Velocity profile for different values of magnetic field parameter at time t = 0.4 and 0.8.

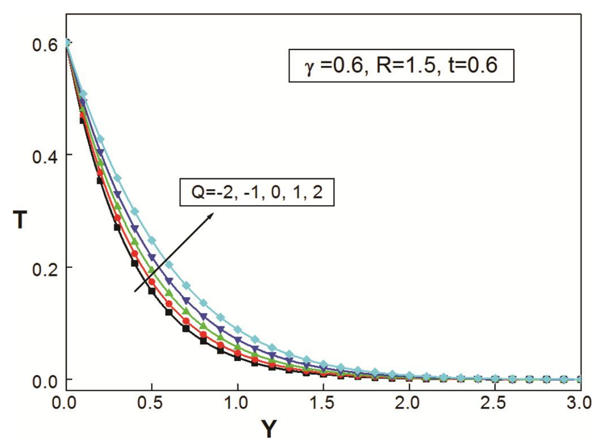

Fig. 7 – Temperature profile for different values of heat source parameter.

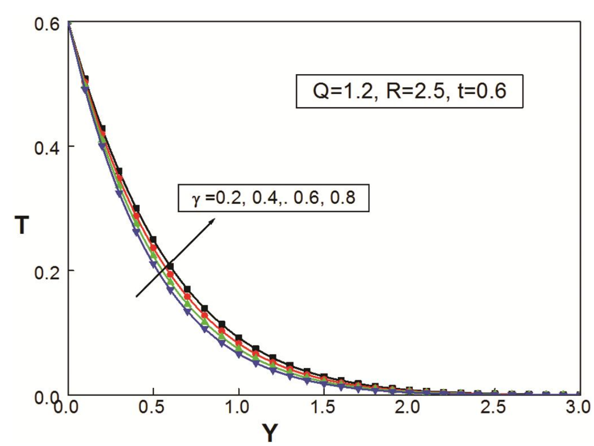

Fig. 8 – Temperature profile for different values of suction parameter.

heat source/sink on Nusselt number against time is shown in Fig. 13 at γ =0.6, R=1.5. This shows that Nusselt number increases with increase in heat sink but decreases with increase in heat source. Figure 14 showing the effects of radiation parameter and suction parameter at Q=1.5, reveals that Nusselt number increases with increased values of suction parameter as well as radiation parameter.

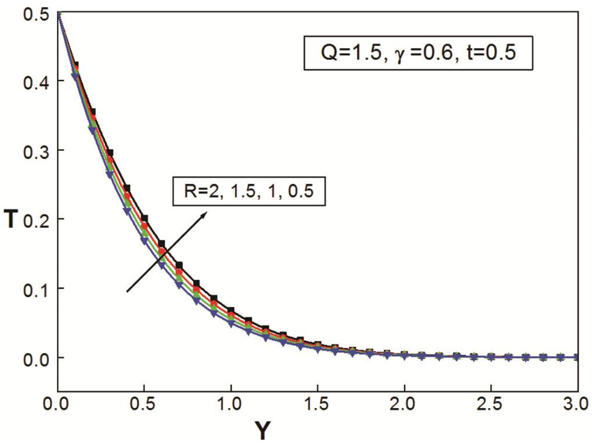

Fig. 9 – Temperature profile for different values of radiation parameter.

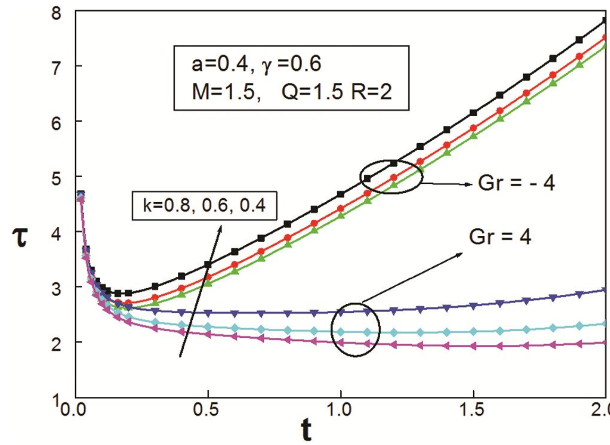

Fig. 12 – Skin friction for different values of permeability parameter at Gr = - 4 and 4.

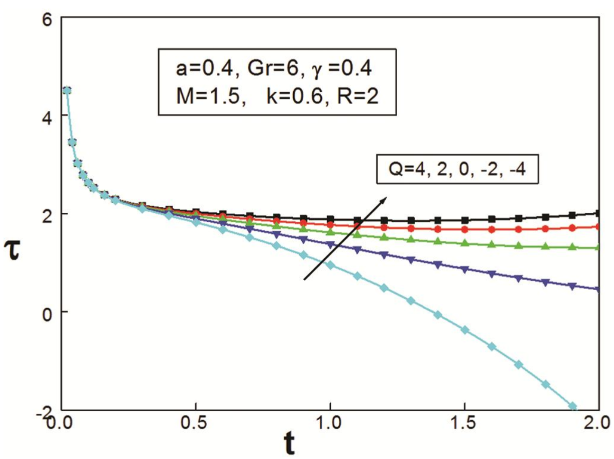

Fig. 10 – Skin friction for different values of heat source parameter.

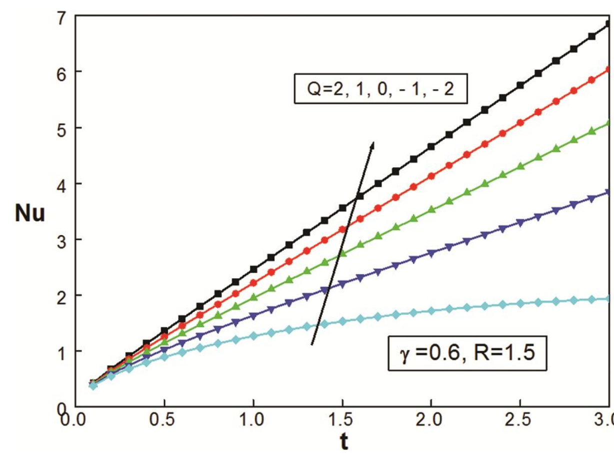

Fig. 13 – Nusselt number for different values of heat source parameter.

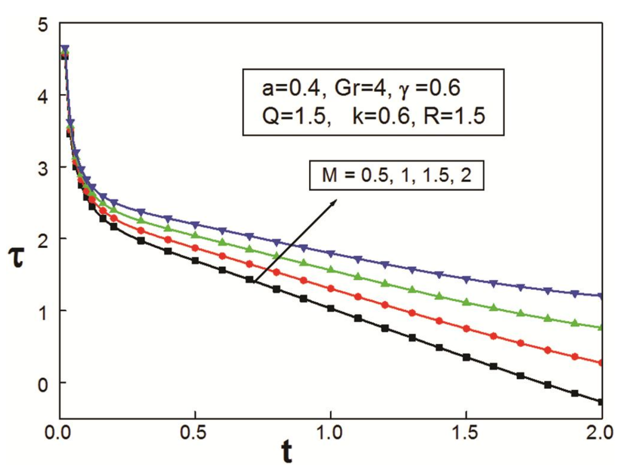

Fig. 11 – Skin friction for different values of magnetic field parameter.

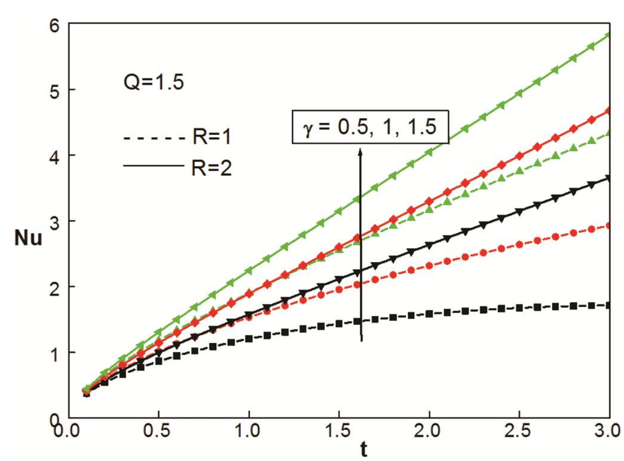

Fig. 14 – Nusselt number for different values of suction parameter.

5 Conclusions

The analytical study on unsteady 1-D free convection flow of a viscous incompressible and electrically conducting liquid over an exponentially accelerated vertical porous sheet in a porous medium under the influence of variable temperature is investigated theoretically. The observations of the present study are as follows:

(i) Velocity increases with increase in permeability parameter k but decreases with increase in M or γ or R.
(ii) Temperature increases with increase τ but decreases with increase in γ or R.
(iii) Skin friction increases with increase in M or γ or R but decreases with increase in k.
(iv) Rate of heat transfer increases with increase in R or γ.

Nomenclature

a' accelerating parameter
a dimensionless accelerating parameter
a^* absorption coefficient
C_p specific heat at constant pressure
B_0 transverse magnetic field strength
Gr Grashof number
g acceleration due to gravity
κ thermal conductivity of the fluid
k' permeability parameter
k dimensionless permeability parameter
M magnetic field parameter
Nu Nusselt number
Pr Prandtl number
q_r radiative heat flux in the y direction
R radiation parameter
Q heat source parameter
t' time
t dimensionless time
T' temperature
T dimensionless temperature
T'_w temperature of the plate
T'_∞ temperature of the fluid far away from the plate
u' x-component of velocity
u'_0 velocity of the plate
U dimensionless velocity
v' y-component of velocity
y' coordinate axis normal to the plate
Y dimensionless coordinate axis normal to the plate

Greek symbols

β volumetric coefficient of thermal expansion
γ suction parameter
ν kinematic viscosity
ρ fluid density
σ electrical conductivity of fluid.

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