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HEAT SOURCE EFFECTS ON MHD FREE CONVECTION FLOW PAST A VERTICAL PLATE WITH RAMPED WALL TEMPERATURE THROUGH A POROUS MEDIUM

K. Jonah Phillip[1], V. Rajesh[2*] and S. Vijaya Kumar Varma[3]

[1]Department of Mathematics, S.V. University, Tirupathi-517502 (A.P), India
E-mail: j.philliph27@gmail.com

[2]Department of Engineering Mathematics, GITAM University, Hyderabad-502329 (A.P), India
E-mail: v.rajesh.30@gmail.com

[3]Department of Mathematics, S.V. University, Tirupathi-517502 (A.P), India

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ABSTRACT

An analytical study is performed to examine the effects of temperature dependent heat source on the unsteady free convection flow of a viscous incompressible electrically conducting fluid past an infinite vertical plate containing a ramped type temperature profile with respect to time under the action of a uniform magnetic field through porous medium. The temperature of the plate is raised or lowered to $T'_\infty + \left(T'_w - T'_\infty\right)\dfrac{t'}{t_0}$ *when* $t' \le t_0$, *and thereafter, for* $t' > t_0$, *the temperature of the plate is maintained at the constant temperature* T'_w. *The exact solutions of the energy and momentum equations, under the usual Boussinesq approximation have been obtained in closed form by the Laplace transform technique. The influence of the various parameters, entering into the problem, on the velocity field, temperature field, Skin friction and Nusselt number is extensively discussed with the help of graphs.*

Keywords: *MHD, free convection, porous medium, heat source, ramped temperature, laplace transform technique.*

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1 INTRODUCTION

Fluid currents formed in a fluid-saturated porous medium during convective heat transfer have many important applications, such as oil and gas production, cereal grain storage, geothermal energy, and porous insulation. The study of natural convection through porous medium also throws some light on the influence of environment-like temperature and pressure on the germination of seeds. In many situations the influence of heat transfer on the hydro magnetic flow near the vertical plate is encountered e.g.., the cooling of nuclear reactor with electrically-conducting coolants such as liquid sodium and mercury (Rath and parida [1]). Raptis et al. [2] have studied the steady free-convection flow and mass transfer through a porous medium bounded by an infinite vertical plate for the flow near the plate, by using the model of Yamamoto and Iwamura [3] for the generalized Darcy’s law. Gebhart and pera [4] have studied the laminar flows which arise in fluids due to the interaction of the force of gravity and density differences caused by the simultaneous diffusion of thermal energy and of chemical species. But in these papers the effects of temperature-dependent heat sources have not been taking into account. Such a situation exists in many industrial or technological applications, solar energy problems, or in problem of space sciences. From this point of view, Raptis and Tzivanidis [5] have studied the effects of mass transfer, free convection currents, and heat sources on the Stoke’s problem for an infinite vertical plate. Basant kumar Jha and Ravindra Prasad [6] have studied the effects of heat source on MHD free-convection and mass transfer flow through a porous medium.

Several investigations were performed using both analytical and numerical methods under different thermal conditions which are continuous and well-defined at the wall. Practical problems often involve wall conditions that are non-uniform or arbitrary. To understand such problems, it is useful to investigate problems subject to step change in wall temperature. Keeping this in view, Schetz [7] made an attempt to develop an approximate analytical model for free convection flow from a vertical plate with discontinuous wall temperature conditions. Several investigations were continued on this problem using an experimental technique [8], numerical methods [9], and by using series expansions [10, 11]. Lee and Yovanovich [12] presented a new analytical model for the laminar natural convection from a vertical

***Corresponding author: V. Rajesh[2*], *E-mail: v.rajesh.30@gmail.com**

plate with step change in wall temperature. The validity and accuracy of the model is demonstrated by comparing with the existing results. Chandran et al. [13] have presented an analytical solution to the unsteady natural convection flow of an incompressible viscous fluid near a vertical plate with ramped wall temperature and they have compared the results with constant temperature. Recently, Saha et al. [14] investigated the natural convection boundary layer adjacent to an inclined semi-infinite flat plate subjected to ramp heating. The flow development from the start-up to an eventual steady state has been described based on scaling analysis and verified by numerical simulations.

The objective of the present paper is to study the effects of heat source on the unsteady MHD free convection flow of an electrically conducting viscous incompressible fluid past an infinite vertical plate containing a ramped type temperature profile with respect to time through a porous medium. The dimensionless governing equations are solved using the Laplace transform technique. The solutions are in terms of exponential, unit step and complementary error function.

2. MATHEMATICAL ANALYSIS

The unsteady flow of an incompressible and electrically conducting viscous fluid past an infinite vertical plate through porous medium in the presence of heat source is considered. A transverse magnetic field of uniform strength B_o is assumed to be applied normal to the plate. The induced magnetic field is neglected as the magnetic Reynolds number of the flow is taken to be very small. The x' -axis is taken along the plate in the vertically upward direction and y'-axis is taken normal to the plate. Initially for time $t' \le 0$, both the fluid and the plate are at rest and at the constant temperature T'_∞. At time $t' > 0$, the temperature of the plate is raised or lowered to $T'_\infty + \left(T'_w - T'_\infty\right)\frac{t'}{t_0}$ when $t' \le t_0$, and thereafter, for $t' > t_0$, the temperature of the plate is maintained at the constant temperature T'_w. It is assumed that the effect of viscous dissipation is negligible. Applying the Boussinesq approximation, the unsteady flow is governed by the following equations.

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

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} + Q' \tag{2}$$

With the initial and boundary conditions

$$u' = 0,\ T' = T'_\infty, \text{ for all } y' \ge 0 \quad \text{and} \quad t' \le 0$$

$$u' = 0 \text{ at } y' = 0 \quad \text{for } t' > 0$$

$$T' = T'_\infty + \left(T'_w - T'_\infty\right)\frac{t'}{t_0} \text{ at } y' = 0 \quad \text{for} \quad 0 < t' \le t_0$$

$$T' = T'_w \text{ at } y' = 0 \text{ for } \quad t' > t_0$$

$$u' = 0,\quad T' \to T'_\infty \text{ as } y' \to \infty \quad \text{for} \quad t' > 0 \tag{3}$$

On introducing the following non-dimensional quantities:

$$u = u'\sqrt{\frac{t_0}{\nu}},\quad t = \frac{t'}{t_0},\quad y = \frac{y'}{\sqrt{\nu t_0}},\quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\quad P_r = \frac{\rho\nu C_p}{\kappa},\ M = \frac{\sigma t_0 B_0^2}{\rho},$$

$$S = \frac{Q t_0 \nu}{\kappa},\quad K = \frac{K'}{\nu t_0} \tag{4}$$

in equations (1) and (2), leads to

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + \theta - Mu - \frac{u}{K} \tag{5}$$

$$P_r \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} - S\theta \tag{6}$$

According to the above non-dimensionalisation process, the characteristic time t_0 can be defined as

$$t_0 = \frac{\nu^{\frac{1}{3}}}{\left[g\beta\left(T'_w - T'_\infty\right)\right]^{\frac{2}{3}}} \tag{7}$$

The initial and boundary conditions given by equation (3) now become

$$\begin{array}{llll} u = 0,\ \theta = 0 & \text{for all } y \ge 0 & \text{and} & t \le 0 \\ u = 0 & \text{at } y = 0 & \text{for} & t > 0 \\ \theta = t & \text{at } y = 0 & \text{for} & 0 < t \le 1 \\ \theta = 1 & \text{at } y = 0 & \text{for} & t > 1 \\ u \to 0,\ \theta \to 0 & \text{as } y \to \infty & \text{for} & t > 0 \end{array} \tag{8}$$

In the present analysis we have considered the heat generation (absorption) of the type

$$Q' = Q\left(T'_\infty - T'\right) \tag{9}$$

Where $\dfrac{Q'}{\rho C_p}$ is the volumetric rate of heat generation (absorption). All the physical parameters are defined in the nomenclature. The dimensionless governing equations (5) and (6), subject to the boundary conditions (8), are solved by the usual Laplace transform technique and the solutions are derived as follows.

$$\begin{aligned} \theta(y,t) = & \left(\frac{t}{2} + \frac{yP_r}{4\sqrt{S}}\right)\left[\exp\left(y\sqrt{S}\right) erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{\frac{St}{P_r}}\right)\right] \\ & + \left(\frac{t}{2} - \frac{yP_r}{4\sqrt{S}}\right)\left[\exp\left(-y\sqrt{S}\right) erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{\frac{St}{P_r}}\right)\right] \\ & - \left(\frac{t-1}{2} + \frac{yP_r}{4\sqrt{S}}\right)\left[\exp\left(y\sqrt{S}\right) erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}} + \sqrt{\frac{S(t-1)}{P_r}}\right)\right] H(t-1) \\ & - \left(\frac{t-1}{2} - \frac{yP_r}{4\sqrt{S}}\right)\left[\exp\left(-y\sqrt{S}\right) erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}} - \sqrt{\frac{S(t-1)}{P_r}}\right)\right] H(t-1) \end{aligned} \tag{10}$$

$$\begin{aligned} u(y,t) = & \frac{\exp(-ct)}{2d}\left[\exp\left(-y\sqrt{M'-c}\right) erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(M'-c)t}\right)\right. \\ & \left. + \exp\left(y\sqrt{M'-c}\right) erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(M'-c)t}\right)\right] \\ & + \left[\exp\left(-y\sqrt{M'}\right) erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{M't}\right)\right]\left[\frac{-1}{2d} + \frac{ct}{2d} - \frac{cy}{4d\sqrt{M'}}\right] \\ & + \left[\exp\left(y\sqrt{M'}\right) erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{M't}\right)\right]\left[\frac{-1}{2d} + \frac{ct}{2d} + \frac{cy}{4d\sqrt{M'}}\right] \end{aligned}$$

$$-\frac{H(t-1)\exp(-c(t-1))}{2d}\Bigg[\exp\left(-y\sqrt{M'-c}\right)erfc\left(\frac{y}{2\sqrt{t-1}}-\sqrt{(M'-c)(t-1)}\right)$$
$$+\exp\left(y\sqrt{M'-c}\right)erfc\left(\frac{y}{2\sqrt{t-1}}+\sqrt{(M'-c)(t-1)}\right)\Bigg]$$
$$+\left[\exp\left(-y\sqrt{M'}\right)erfc\left(\frac{y}{2\sqrt{t-1}}-\sqrt{M'(t-1)}\right)\right]\left[\frac{H(t-1)}{2d}-\frac{c(t-1)H(t-1)}{2d}+\frac{cyH(t-1)}{4d\sqrt{M'}}\right]$$
$$+\left[\exp\left(y\sqrt{M'}\right)erfc\left(\frac{y}{2\sqrt{t-1}}+\sqrt{M'(t-1)}\right)\right]\left[\frac{H(t-1)}{2d}-\frac{c(t-1)H(t-1)}{2d}-\frac{cyH(t-1)}{4d\sqrt{M'}}\right]$$
$$-\frac{\exp(-ct)}{2d}\Bigg[\exp\left(-y\sqrt{S-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}-\sqrt{\frac{(S-cP_r)t}{P_r}}\right)$$
$$+\exp\left(y\sqrt{S-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}+\sqrt{\frac{(S-cP_r)t}{P_r}}\right)\Bigg]$$
$$+\left[\exp\left(-y\sqrt{S}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}-\sqrt{\frac{St}{P_r}}\right)\right]\left[\frac{1}{2d}-\frac{ct}{2d}+\frac{cyP_r}{4d\sqrt{S}}\right]$$
$$+\left[\exp\left(y\sqrt{S}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}+\sqrt{\frac{St}{P_r}}\right)\right]\left[\frac{1}{2d}-\frac{ct}{2d}-\frac{cyP_r}{4d\sqrt{S}}\right]$$
$$+\frac{H(t-1)\exp(-c(t-1))}{2d}\Bigg[\exp\left(-y\sqrt{S-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}}-\sqrt{\frac{(S-cP_r)(t-1)}{P_r}}\right)$$
$$+\exp\left(y\sqrt{S-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}}+\sqrt{\frac{(S-cP_r)(t-1)}{P_r}}\right)\Bigg]$$
$$+\left[\exp\left(-y\sqrt{S}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}}-\sqrt{\frac{S(t-1)}{P_r}}\right)\right]\left[-\frac{H(t-1)}{2d}+\frac{c(t-1)H(t-1)}{2d}-\frac{cyP_rH(t-1)}{4d\sqrt{S}}\right]$$
$$+\left[\exp\left(y\sqrt{S}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t-1}}+\sqrt{\frac{S(t-1)}{P_r}}\right)\right]\left[-\frac{H(t-1)}{2d}+\frac{c(t-1)H(t-1)}{2d}+\frac{cyP_rH(t-1)}{4d\sqrt{S}}\right] \tag{11}$$

Where $c=\frac{S-M'}{P_r-1},\ d=c(S-M'), M'=M+\frac{1}{K}$ *and* $H(t-1)$ *is the unit step function*

Skin-Friction

We now study skin-friction from velocity field. It is given in non-dimensional form as

$$\tau=\frac{du}{dy}\Bigg]_{y=0} \tag{12}$$

Then from equations (11) and (12), we have

$$\tau = \frac{-\exp(-ct)}{d}\left[\sqrt{M'-c}\,erf\left(\sqrt{(M'-c)t}\right)+\frac{\exp\left(-(M'-c)t\right)}{\sqrt{\pi t}}\right]$$

$$-\left(\frac{ct-1}{d}\right)\left[\sqrt{M'}\,erf\left(\sqrt{M't}\right)+\frac{\exp(-M't)}{\sqrt{\pi t}}\right]-\frac{c}{2d\sqrt{M'}}erf\left(\sqrt{M't}\right)$$

$$+\frac{H(t-1)\exp\left(-c(t-1)\right)}{d}\left[\sqrt{M'-c}\,erf\left(\sqrt{(M'-c)(t-1)}\right)+\frac{\exp\left(-(M'-c)(t-1)\right)}{\sqrt{\pi(t-1)}}\right]$$

$$-\left(\frac{H(t-1)}{d}-\frac{c(t-1)H(t-1)}{d}\right)\left[\sqrt{M'}\,erf\left(\sqrt{M'(t-1)}\right)+\frac{\exp\left(-M'(t-1)\right)}{\sqrt{\pi(t-1)}}\right]$$

$$+\frac{cH(t-1)}{2d\sqrt{M'}}erf\left(\sqrt{M'(t-1)}\right)+\frac{\exp(-ct)}{d}\left[\sqrt{S-cP_r}\,erf\left(\sqrt{\frac{(S-cP_r)t}{P_r}}\right)\right.$$

$$\left.+\sqrt{\frac{P_r}{\pi t}}\exp\left(\frac{-(S-cP_r)t}{P_r}\right)\right]$$

$$-\left[\frac{1-ct}{d}\right]\left[\sqrt{S}erf\left(\sqrt{\frac{St}{P_r}}\right)+\sqrt{\frac{P_r}{\pi t}}\exp\left(\frac{-St}{P_r}\right)\right]+\frac{cP_r}{2d\sqrt{S}}erf\left(\sqrt{\frac{St}{P_r}}\right)$$

$$-\left[\frac{H(t-1)\exp\left(-c(t-1)\right)}{d}\right]\left[\sqrt{S-cP_r}\,erf\left(\sqrt{\frac{(S-cP_r)(t-1)}{P_r}}\right)+\sqrt{\frac{P_r}{\pi(t-1)}}\exp\left(\frac{-(S-cP_r)(t-1)}{P_r}\right)\right]$$

$$-\left[\frac{c(t-1)H(t-1)}{d}-\frac{H(t-1)}{d}\right]\left[\sqrt{S}erf\left(\sqrt{\frac{S(t-1)}{P_r}}\right)+\sqrt{\frac{P_r}{\pi(t-1)}}\exp\left(\frac{-S(t-1)}{P_r}\right)\right]$$

$$-\frac{cP_rH(t-1)}{2d\sqrt{S}}erf\left(\sqrt{\frac{S(t-1)}{P_r}}\right) \qquad (13)$$

Nusselt Number

From the temperature field, we now study the rate of heat transfer, which is given in non-dimensional form as

$$N_u = \left.\frac{-d\theta}{dy}\right]_{y=0} \qquad (14)$$

From equations (10) and (14) we have

$$N_u = \frac{P_r}{2\sqrt{S}}erf\left(\sqrt{\frac{St}{P_r}}\right)+t\left[\sqrt{S}erf\left(\sqrt{\frac{St}{P_r}}\right)+\sqrt{\frac{P_r}{\pi t}}\exp\left(\frac{-St}{P_r}\right)\right]$$

$$-\frac{P_rH(t-1)}{2\sqrt{S}}erf\left(\sqrt{\frac{S(t-1)}{P_r}}\right) \qquad (15)$$

$$-(t-1)H(t-1)\left[\sqrt{S}erf\left(\sqrt{\frac{S(t-1)}{P_r}}\right)+\sqrt{\frac{P_r}{\pi(t-1)}}\exp\left(\frac{-S(t-1)}{P_r}\right)\right]$$

3 RESULTS AND DISCUSSIONS

In order to get the physical insight into the problem, numerical computations are carried out for different physical parameters S (Heat source parameter), Pr (prandtl number), t (time), M (Magnetic parameter) and K (Permeability parameter) upon the nature of the flow and transport. The values of the prandtl number Pr are chosen as Pr =0.71(air) and Pr =7(water).

Figures (1) and (2) represent the temperature profiles for different values of S (Heat source parameter) at t=0.5 and t=1.3 for both air (Pr =0.71) and water (Pr =7) respectively. It is observed that the temperature decreases with an increase in S for both air and water. It is also observed that the temperature is maximum near the plate and decreases away from the plate and finally takes asymptotic value for all values of S.

Figure 1. Temperature Profiles when Pr=0.71

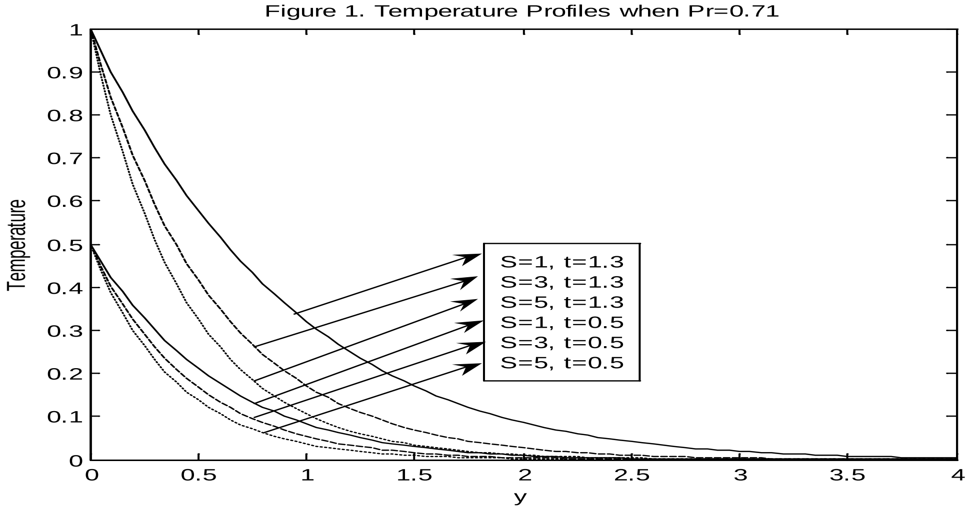
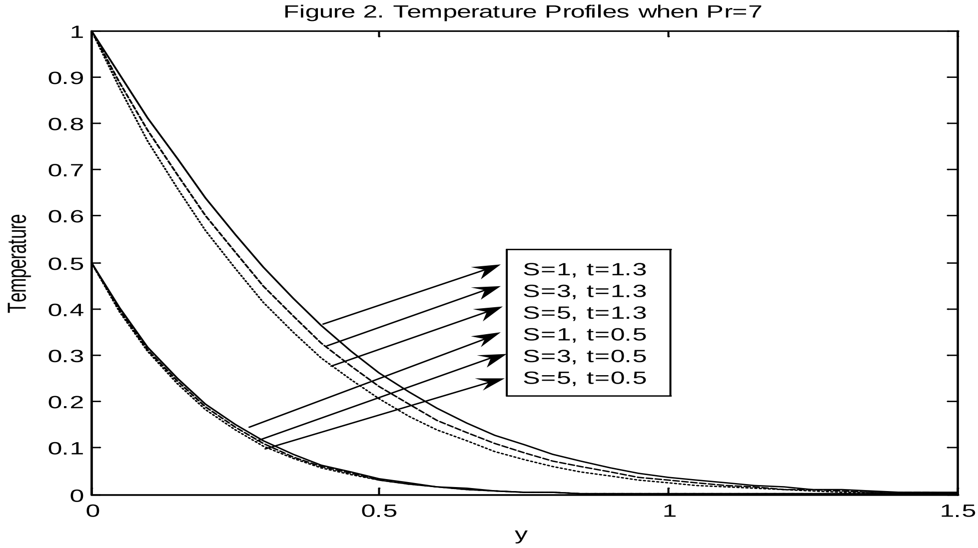
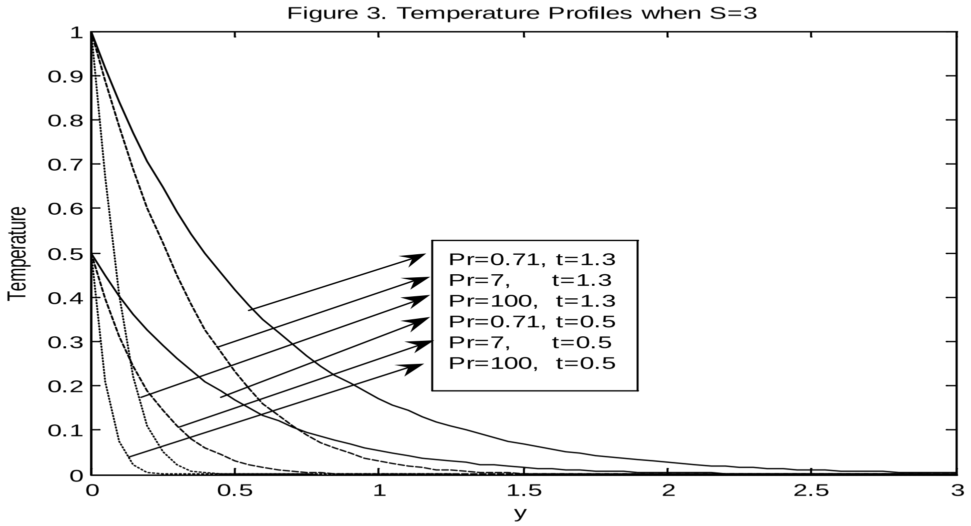


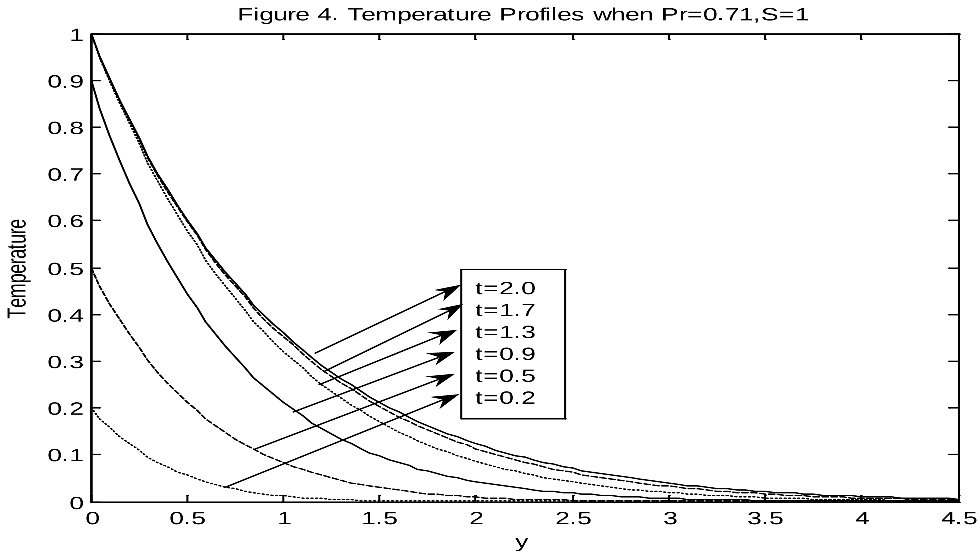
Figure 2. Temperature Profiles when Pr=7

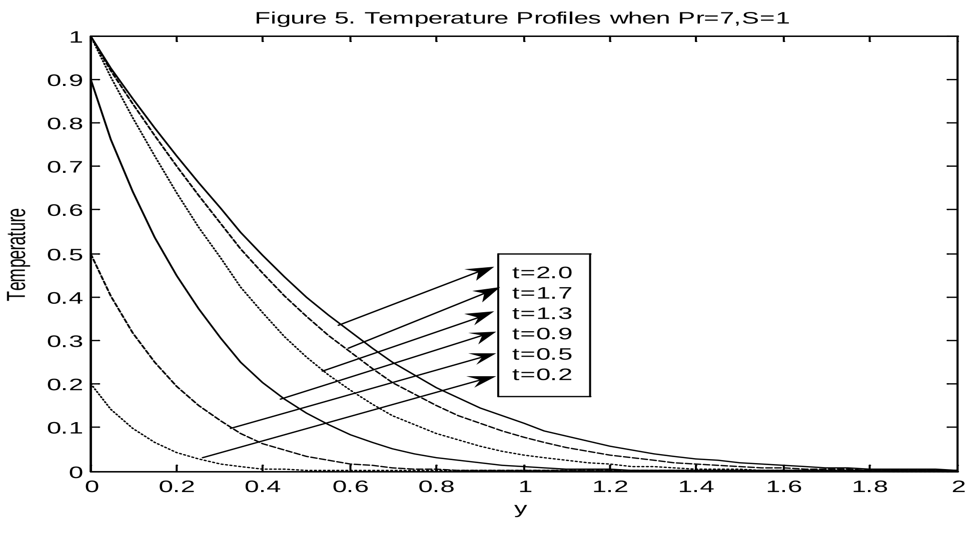


Figures (3) reveals temperature variations with Pr (Prandtl number) at t=0.5 and t=1.3. The temperature is observed to decrease with an increase in Pr. It is also observed that the temperature is maximum near the plate and decreases away from the plate and finally takes asymptotic value for all values of Pr.



Figures (4) and (5) display the effects of t (time) on the temperature field for the cases of air (Pr =0.71) and water (Pr =7) respectively. It is found that the temperature increases with an increase in t (time) for both air and water. It is also found that the temperature decreases with y from its ramped value on the plate to its free stream value for all values of time t.





The velocity profiles for different values of S (Heat source parameter) are presented in figures (6) and (7) at t=0.5 and t=1.3 for both air (Pr =0.71) and water (Pr =7) respectively. The velocity is found to decrease with an increase in S for both air and water. It is also found that the velocity increases with y near the plate and becomes maximum and then decreases away from the plate and finally takes asymptotic value for all values of S.

Figure 6. Velocity Profiles when Pr=0.71,M=1,K=1

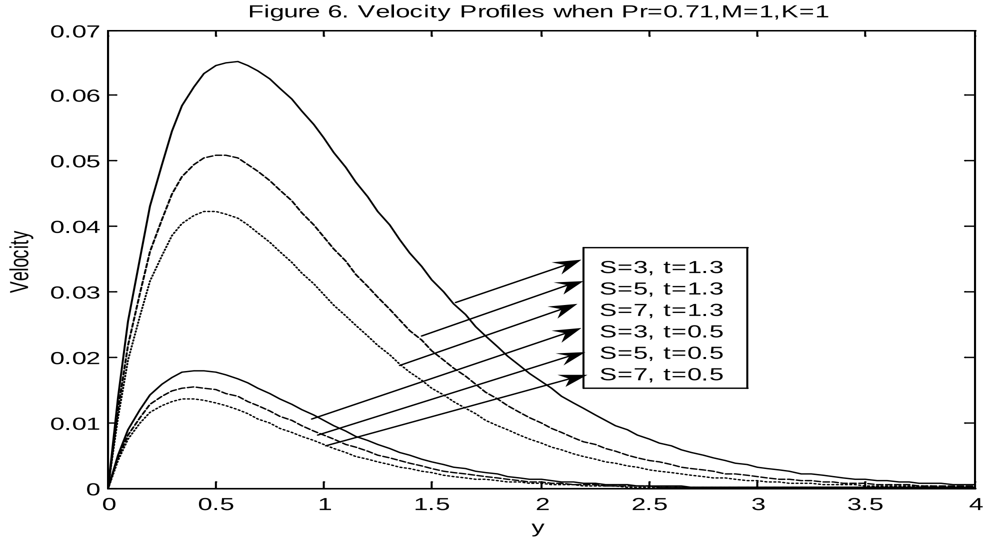
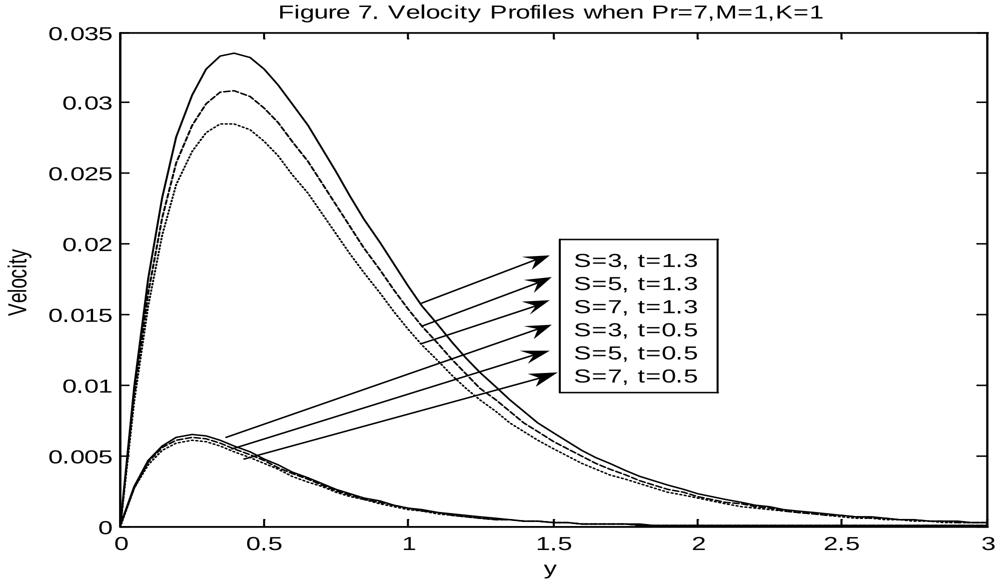


Figure 7. Velocity Profiles when Pr=7,M=1,K=1



Figures (8) and (9) illustrate the influences of M (Magnetic parameter) on the velocity field at t=0.5 and t=1.3 for both air (Pr =0.71) and water (Pr =7) respectively. It is observed that the velocity decreases with an increase in M (Magnetic parameter) for both air and water. It is also observed that the velocity increases with y near the plate and becomes maximum and then decreases away from the plate and finally takes asymptotic value for all values of M.

Figure 8. Velocity Profiles when Pr=0.71,S=5,K=1

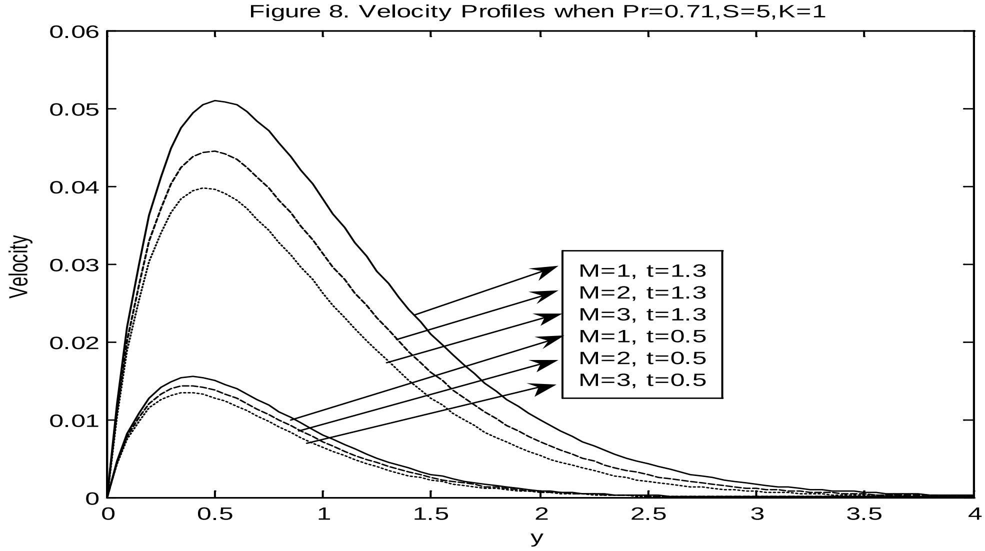


Figure 9. Velocity Profiles when Pr=7,S=5,K=1

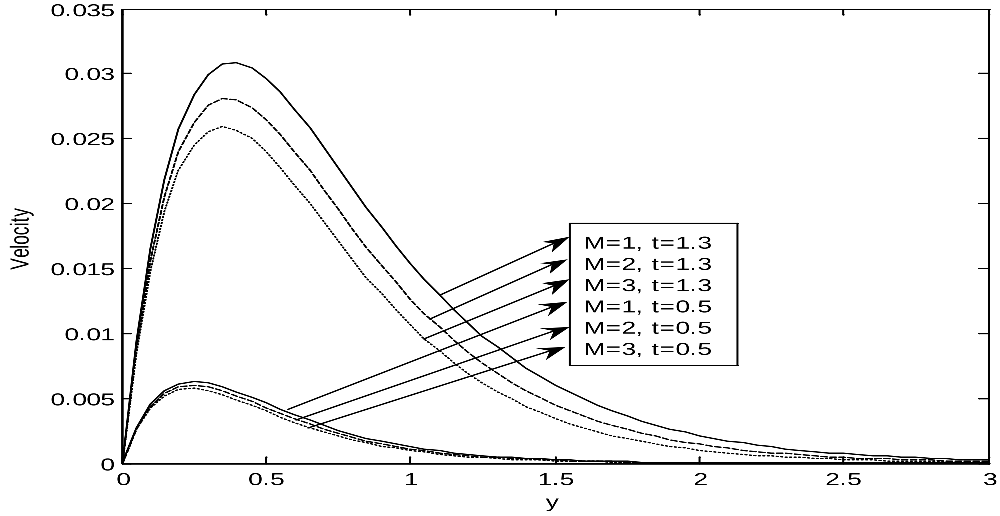
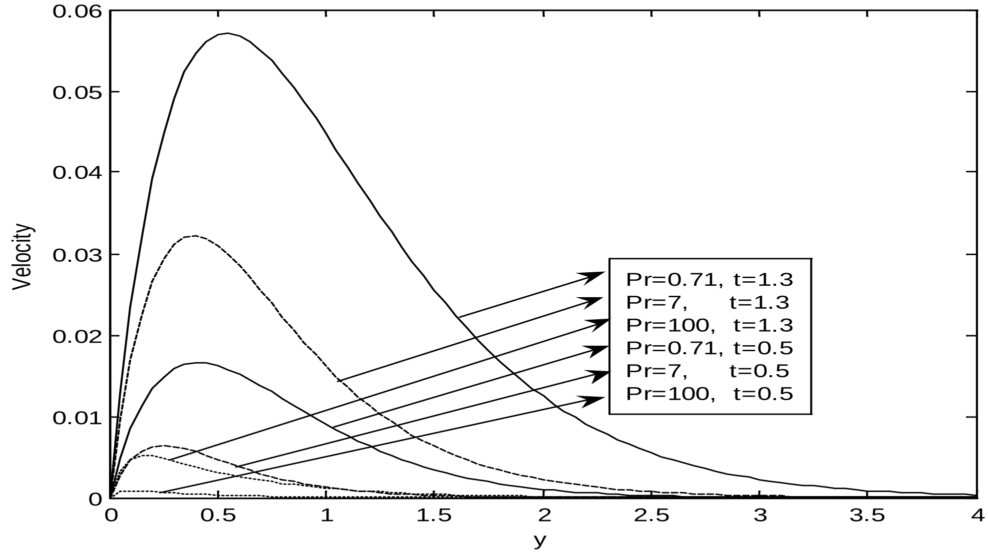


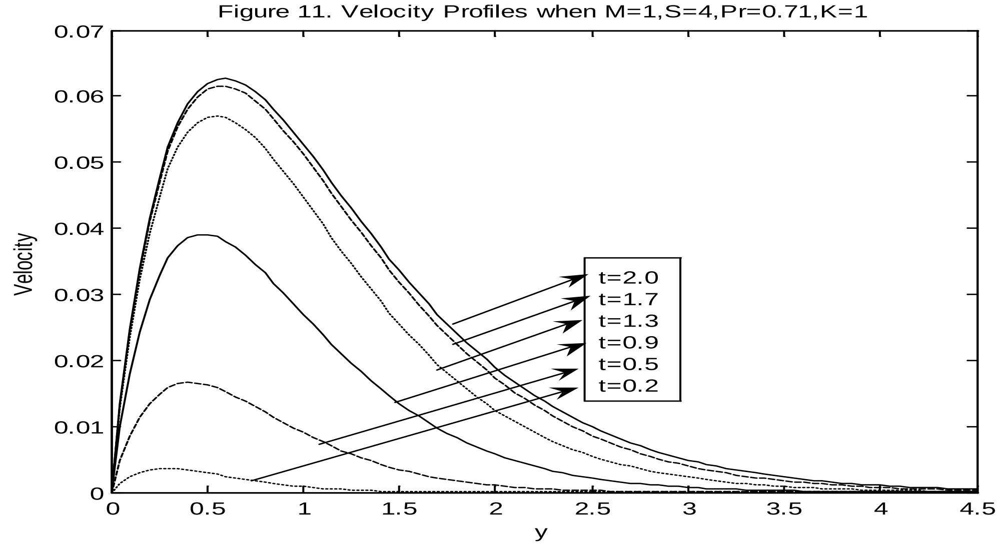
Figure (10) reveals velocity variations with Pr (Prandtl number) at t=0.5 and t=1.3. The velocity is observed to decrease with an increase in Pr. It is also observed that the velocity increases with y near the plate and becomes maximum and then decreases away from the plate and finally takes asymptotic value for all values of Pr.

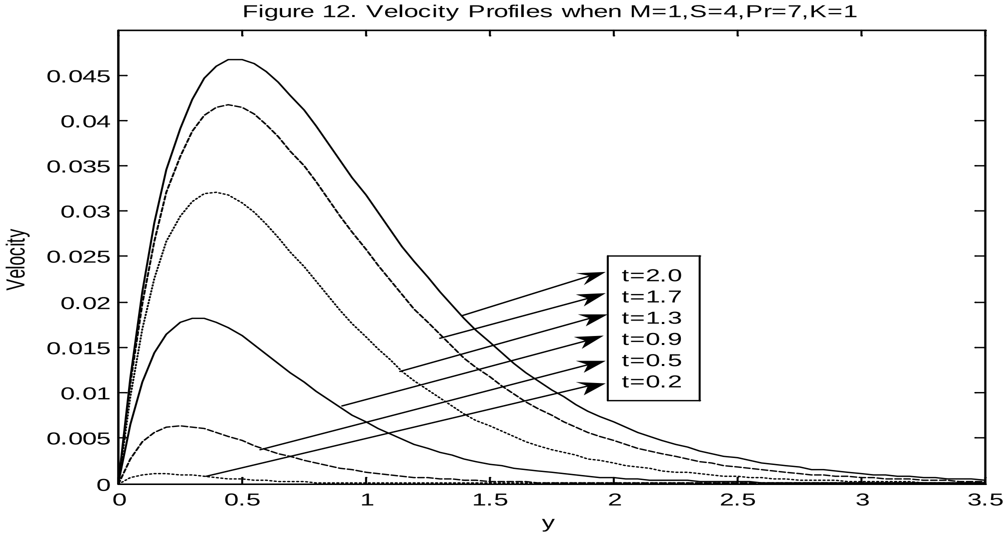
Figure 10. Velocity Profiles when M=1,S=4,K=1



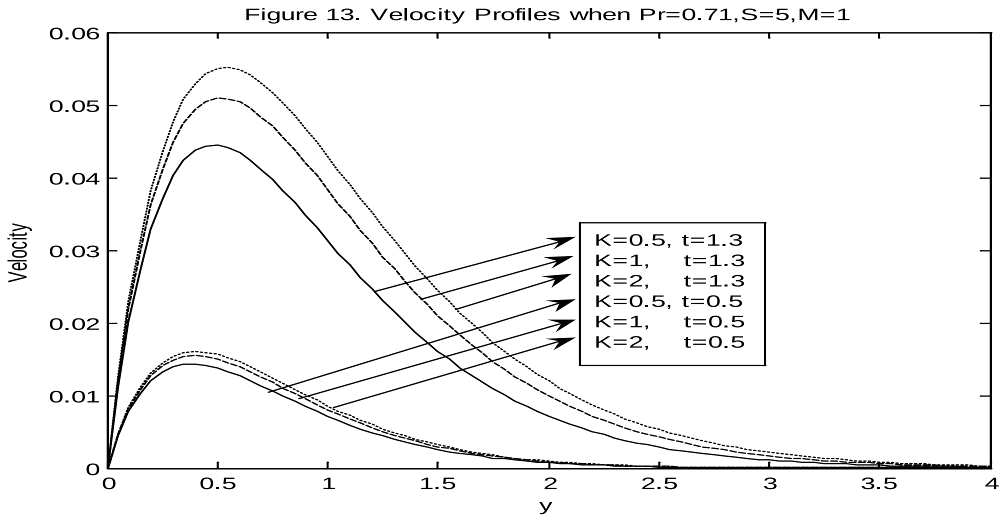
Figures (11) and (12) display the effects of t (time) on the velocity field for the cases of air (Pr =0.71) and water (Pr =7). It is observed that the velocity increases with an increase in t (time) for both air and water. It is also observed that the velocity increases with y near the plate and becomes maximum and then decreases away from the plate and finally takes asymptotic value for all values of time t. Moreover the points of maxima on the curves get shifted to the right as t increases.

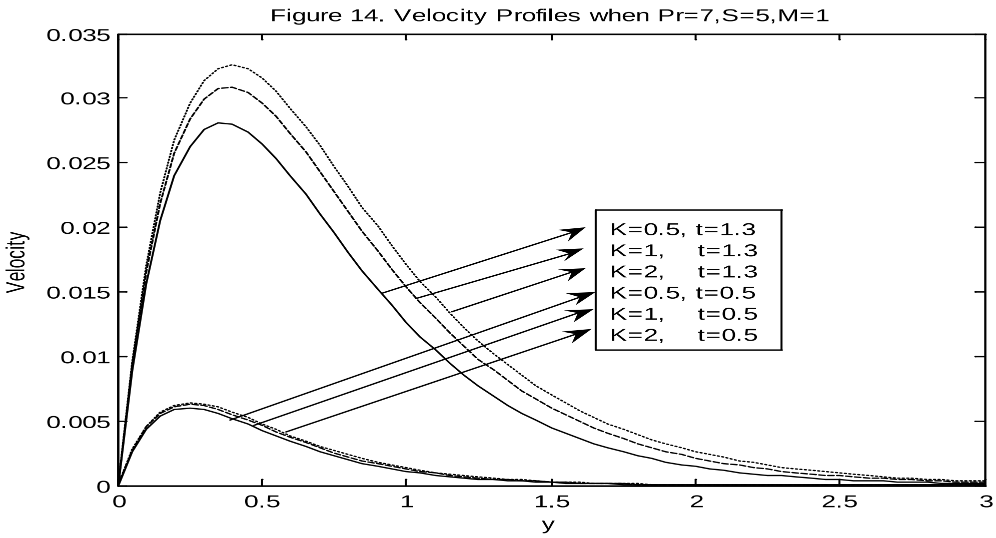
Figure 11. Velocity Profiles when M=1,S=4,Pr=0.71,K=1





Figures (13) and (14) illustrate the influences of K (Permeability parameter) on the velocity field at t=0.5 and t=1.3 for both air (Pr =0.71) and water (Pr =7) respectively. It is observed that the velocity increases with an increase in K (Permeability parameter) for both air and water. It is also observed that the velocity increases with y near the plate and becomes maximum and then decreases away from the plate and finally takes asymptotic value for all values of K.





Nusselt number is presented in figures (15), (16) and (17) against t (time). From figures (15) and (16), it is found that the nusselt number increases with an increase in S for both air (Pr =0.71) and water (Pr =7) respectively. It is also found that the nusselt number increases with t for $0 < t < 1$, and decreases for $t > 1$, for all values of the Heat Source parameter S. From figure (17), the nusselt number is found to increase with an increase in Pr. It is also found that the nusselt number increases with t for $0 < t < 1$ and decreases for $t > 1$, for all values of the prandtl number Pr.

Figure 15. Nusselt number when Pr=0.71

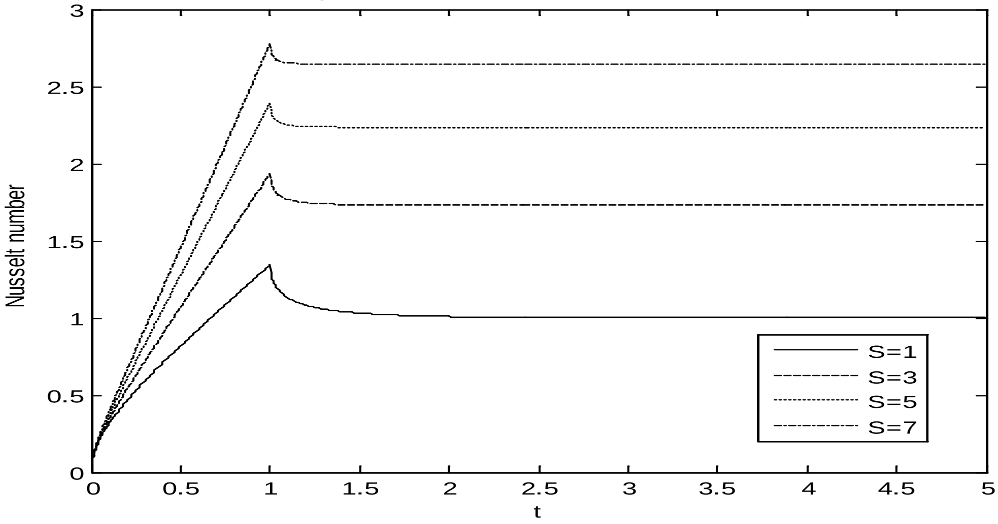


Figure 16. Nusselt number when Pr=7

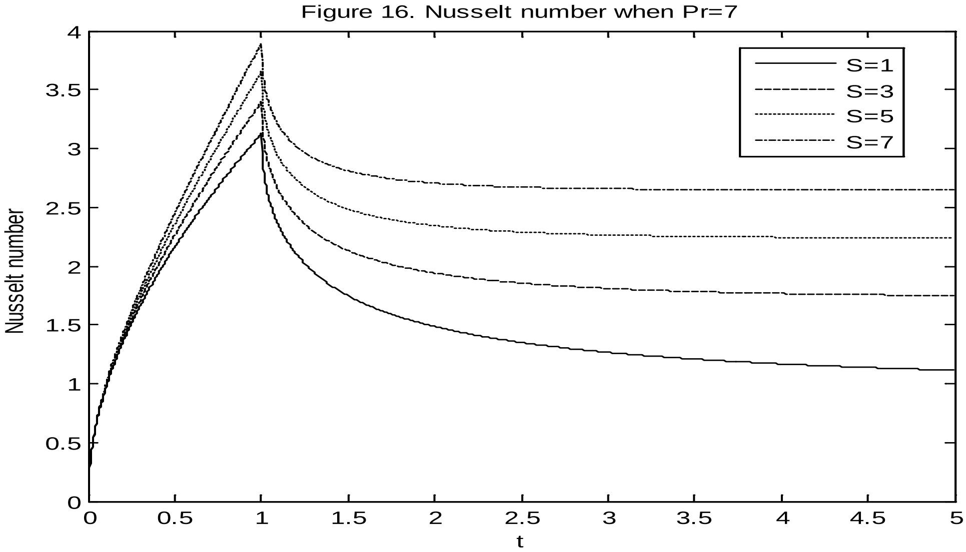
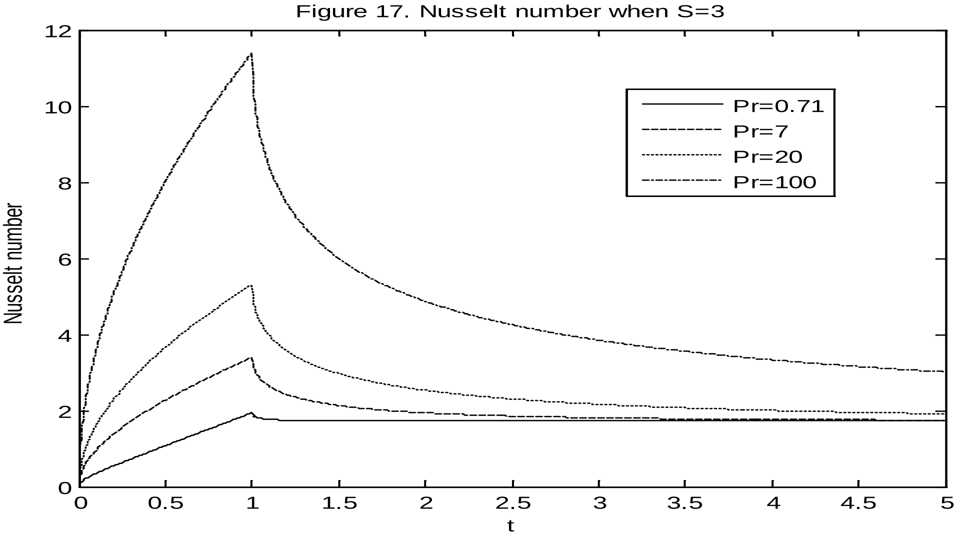
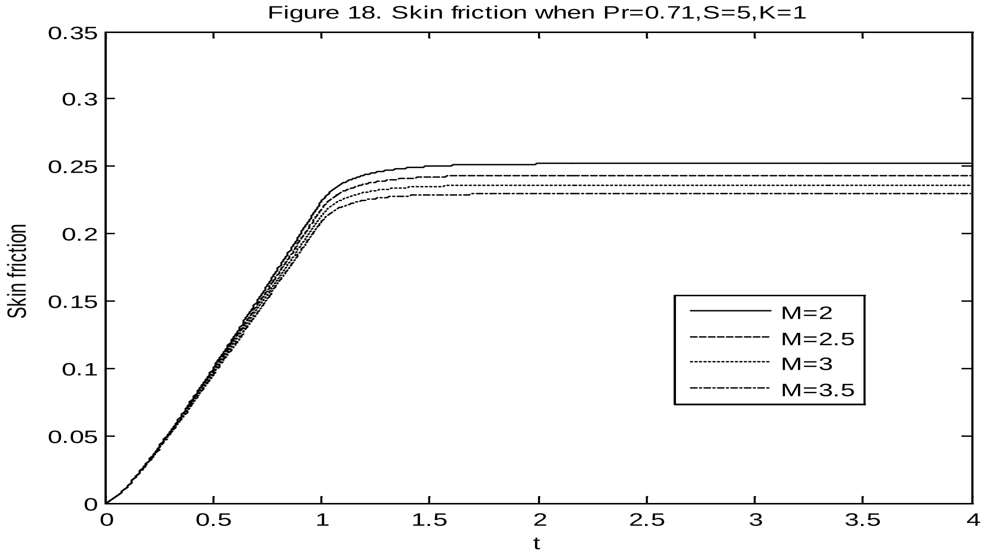
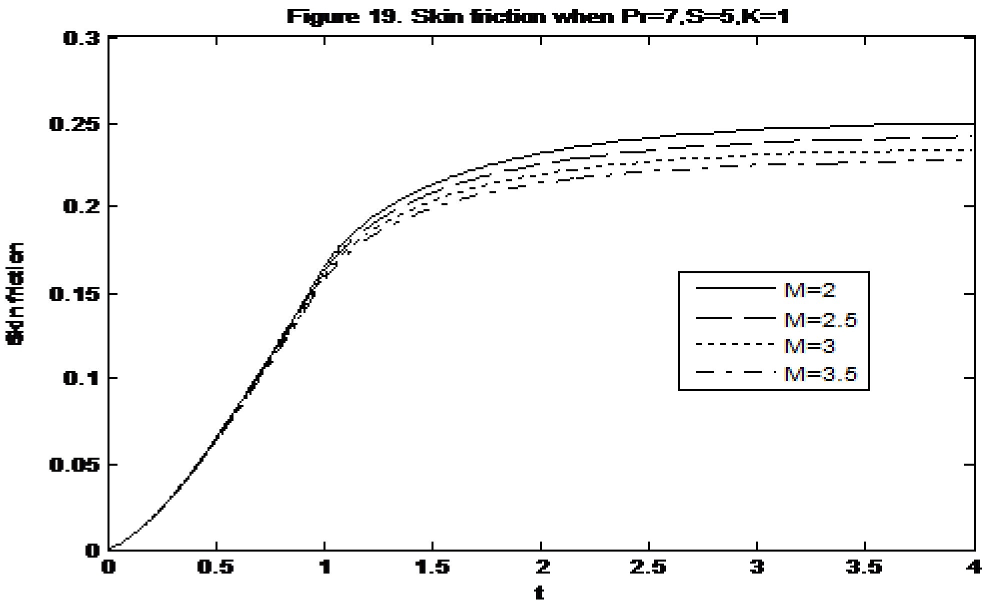


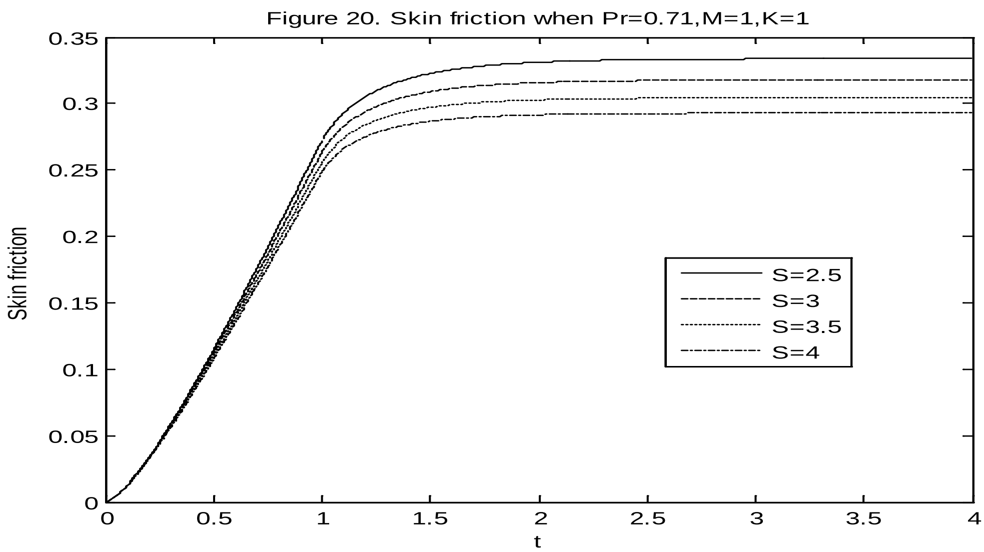
Figure 17. Nusselt number when S=3



Skin friction is studied in figures (18) to (24) against time t. From figures (18) to (21), (23) and (24), it is observed that the skin friction decreases with an increase in M (Magnetic parameter) or S (Heat source parameter) and increases with an increase in K (Permeability parameter) for both air (Pr =0.71) and water (Pr =7). It is also observed that the skin friction increases with t (time) for all values of M, S and K. From figure (22), it is found that the skin friction decreases with an increase in Pr. It is also found that the skin friction increases with t (time) for all values of the Prandtl number Pr.







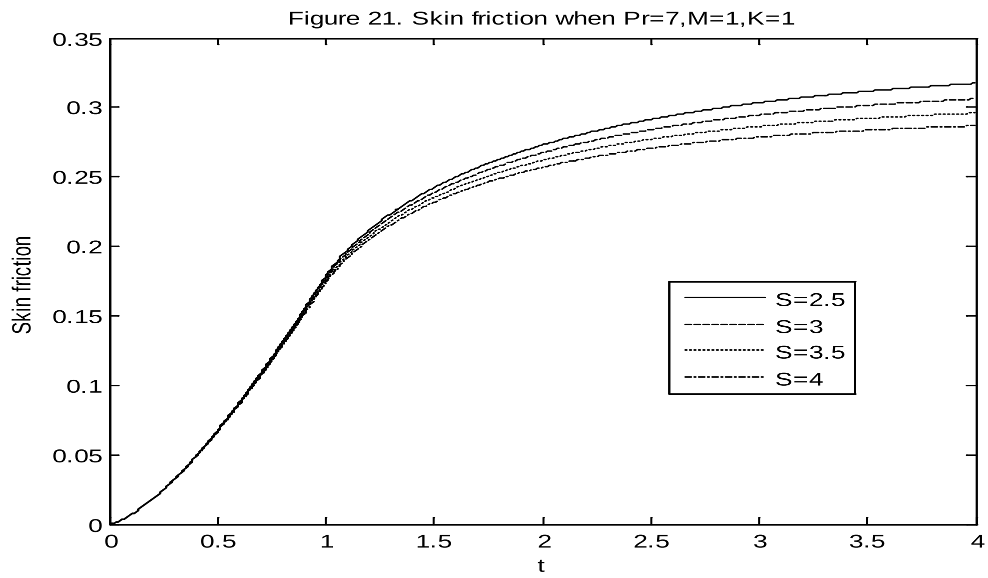


Figure 21. Skin friction when Pr=7,M=1,K=1
Skin friction
t
S=2.5
S=3
S=3.5
S=4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.5
1
1.5
2
2.5
3
3.5
4

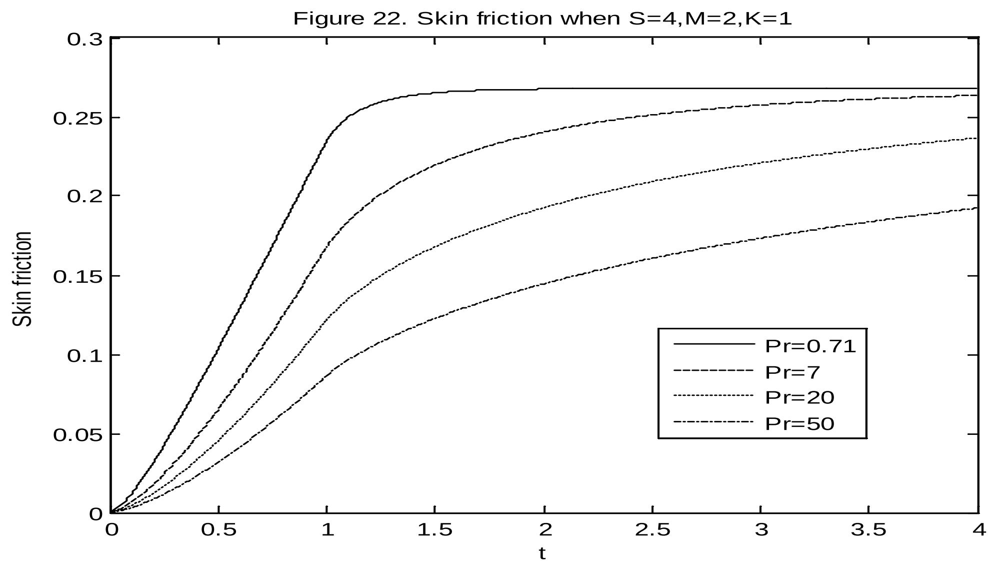


Figure 22. Skin friction when S=4,M=2,K=1
Skin friction
t
Pr=0.71
Pr=7
Pr=20
Pr=50
0
0.05
0.1
0.15
0.2
0.25
0.3
0.5
1
1.5
2
2.5
3
3.5
4

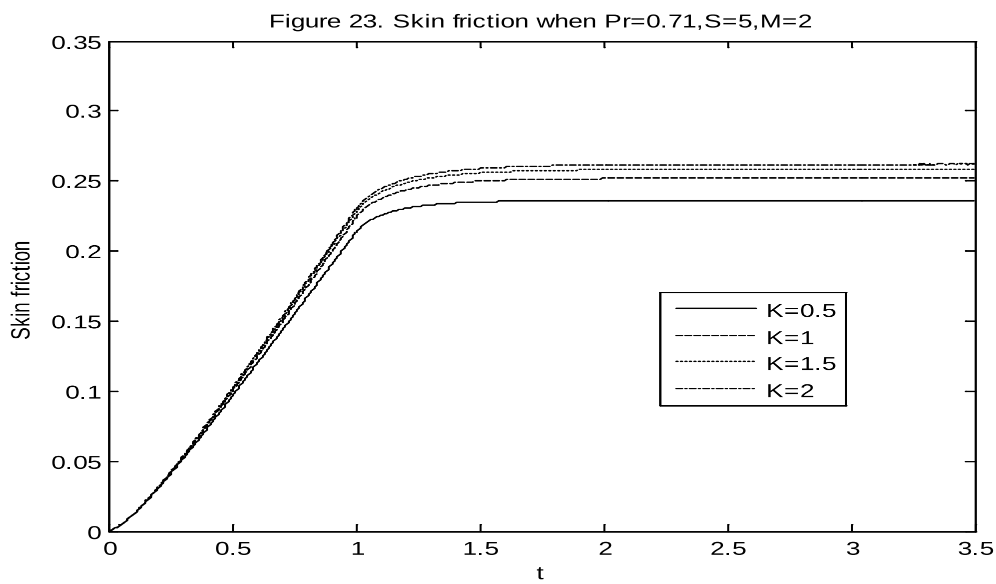
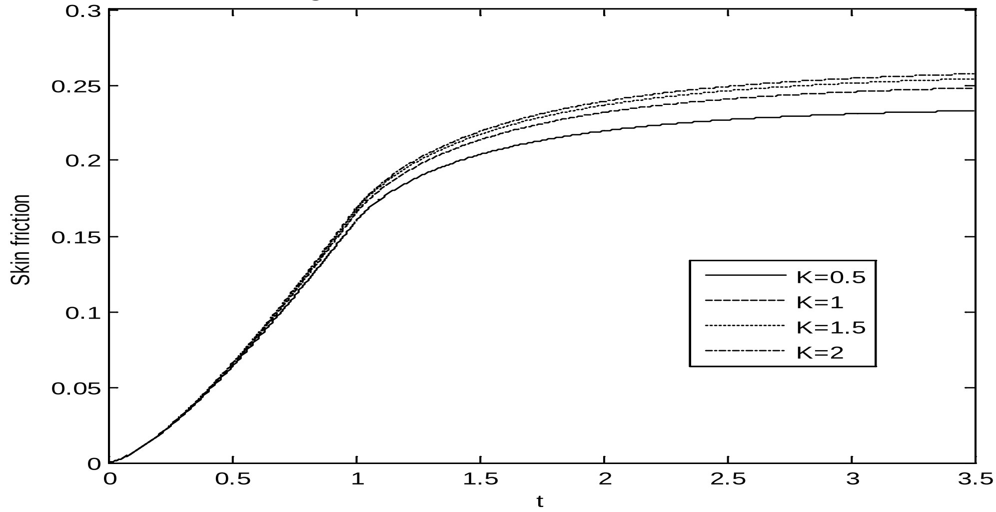


Figure 23. Skin friction when Pr=0.71,S=5,M=2
Skin friction
t
K=0.5
K=1
K=1.5
K=2
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.5
1
1.5
2
2.5
3
3.5



APPENDIX

Nomenclature

t_0	Characteristic time
y'	Coordinate axis normal to the plate
y	Dimensionless coordinate axis normal to the plate
u	Dimensionless velocity
B_0	External magnetic field
P_r	Prandtl number
C_p	Specific heat at constant pressure
T'_∞	Temperature of the fluid far away from the plate
T'	Temperature of the fluid near the plate
T'_w	Temperature of the plate
κ	Thermal conductivity of the fluid
t'	Time
u'	Velocity of the fluid in the x' -direction
g	Acceleration due to gravity
K	permeability parameter
M	Magnetic field parameter
S	Heat source parameter
t	Dimensionless time

Greek symbols

$H(t-1)$ is the unit step function

μ	Coefficient of viscosity
$erfc$	Complementary error function
ρ	Density of the fluid
τ	Dimensionless skin friction
θ	Dimensionless temperature
σ	Electric conductivity
erf	Error function
ν	Kinematic viscosity
N_u	Nusselt number
α	Thermal diffusivity
β	Volumetric coefficient of thermal expansion

Subscripts

w	Conditions on the wall
∞	Free stream conditions

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